OXFORD INSTITUTE FOR ENERGY STUDIES

Have Low Oil Prices Reversed The Decline in Energy Demand?

A Case Study for the UK

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1 INTRODUCTION

Total energy demand and the product composition of energy consumption have changed considerably following the two oil crises of the 1970s. Although total primary energy consumption in the OECD was higher in 1987 than it had been at any time previously, its rate of growth had fallen considerably. The average rate of growth of 5 per cent per annum during the 1960s was reduced to 1.9 per cent in the 1970s and further to only 0.5 per cent over the period 1980-7. For oil, the development was somewhat different. In 1987 total oil consumption was 15 per cent below its peak of 1978, and the growth rate was reduced from nearly 8 per cent per annum in the 1960s to 1.4 per cent during the 1970s and to an average annual decline of 1 per cent during the 1980s. Some of this change is, of course, explained by changes in the level of economic activity, as the growth rate of real GDP during the last two decades was only half that of the 1960s. However, while the energy-GDP ratio was 4 per cent higher in 1970 than in 1960, and the oil-GDP ratio 32 per cent higher, a substantial and continual decline has been apparent from the early 1970s onwards. Over the period 1970-87 the energy intensity of GDP fell by 23 per cent, and the oil intensity by 35 per cent. Although oil intensity began its decline with the first oil price shock, the downward trend in *energy* intensity pre-dated this by a few years. A plausible explanation for this may be found in the structural changes in the economies of the OECD countries, and particularly in the shift in production from heavy industries to the service sector. Although this movement towards lower energy intensity would have continued regardless of energy prices, there is no doubt that the oil price shocks of the 1970s, and the effects of these on energy prices in general, have speeded up the process of structural change and also provided an impetus for further reductions of energy intensity.

Energy - and even oil - demand began to recover following the collapse of oil prices in 1986. Between 1985 and 1987 oil consumption rose by nearly 3 per cent annually and total energy consumption by 2 per cent annually. The decline in the oil-GDP and energy-GDP ratios continued, however, although at a much slower rate than during the first half of the 1980s. If demand had responded as quickly to the price collapse as it had to the price shock of 1974, and the income elasticity had remained the same, we would expect the decline in energy intensity to be arrested. A partial explanation for this apparent sluggishness in demand may be that the intertemporal adjustment of demand to the price rises of the 1970s is still not complete, so that the initial impact of the price falls are not as apparent as would otherwise be the case. On the other hand, it may be an indication that some of the changes in energy consumption patterns that have taken place over the past fifteen years will not be so quickly reversed and may even have a permanent, dampening effect on energy demand.

The above observations raise the question of the extent to which the reductions in energy demand witnessed during the 1970s and 1980s will be reversed in response to the lower energy prices. At one extreme, if energy demand is completely reversible with respect to price changes, a return to pre-1974 prices will, *ceteris paribus*, restore demand, in the long run, to what it was before the price increases. Of course, if some of the reduction in energy demand was motivated by factors unrelated to prices that are in themselves irreversible (e.g. an exogenous technical change or structural changes in the economy), then demand will still be lower at any given income level, despite the perfect reversibility of demand with respect to prices. However, if the price shocks of the 1970s themselves elicited permanent changes in energy consumption patterns, long-run demand will be different from what it would have been in their absence, regardless of whether or not prices return to the levels of the early 1970s.

There are many reasons why demand may not be perfectly reversible to price changes, even in the long run. The years of high energy prices have served as a catalyst to research efforts into the development of energy-efficient technologies, many of which will remain economically sound despite falling prices. Obviously, these technologies will not be unlearned. In addition, consumers and policy-makers alike may have become more conservation - as well as environment - conscious, so that the efficient use of energy has become more than a purely individual economic problem. It is thus unlikely that energy-saving behaviour or regulation will be totally negated as prices fall. In both of these cases we may see permanent changes in energy demand.

Although most other responses to price rises can be reversed in the long run, the time taken to do so can be exceedingly long. High energy prices have induced both firms and households to make investments in energy conservation, many of which are for all intents and purposes irreversible, since the capital goods involved have long life-spans and no second-hand value. Examples are various types of insulation and retrofitting of industrial machinery, which will not be discarded when prices fall, so that consumption will not increase until the end of their physical lifetime. Although demand will be reversible in the long run, the time required for total adjustment will be greater when prices fall than it was when prices rose. The asymmetrical replacement of capital may be another example. Although price rises may make the earlier retirement of energy-inefficient capital economically sound, the same will not necessarily follow for energy price falls. Because second-hand markets are imperfect, it is unlikely that price decreases will lead to the earlier replacement of efficient capital, unless other costs could be cut considerably as a result. Price expectations and uncertainty also play decisive roles: if consumers believe that the recent price falls are temporary and that prices will once again rise, they may not adjust their energy consumption to the lower price levels, or at least there will be some delay before they begin to do so. These factors, among others, may explain the recent sluggish growth in energy demand noted earlier.

It is the aim of this study to investigate empirically the extent to which the demand reductions of the past fifteen years will be reversed as energy prices fall. Will we soon experience a renewed rapid growth in energy demand or will demand continue to be influenced by the price shocks of the 1970s for some years to come, or perhaps even permanently? As the approach taken will be based on aggregate data and econometric models, this question must be seen in the context of the broader issue of the stability of energy demand relationships, both intertemporally and over wide ranges of price levels and changes. Clearly, if irreversible changes in demand patterns have occurred as a result of the price increases of the 1970s, this would be reflected by the instability of perfectly reversible demand functions when estimated over a period including data from both before the first oil crisis and after the oil price collapse.

Given the aggregation problems involved in considering the OECD as a whole, the analysis is best be done on a country basis. The present study looks at the UK, and is meant to be seen as an empirical case-study of the methodology proposed. Of course it would be unwise to try to apply the results to the OECD as a whole and other countries should be investigated before any generalizations are made.

2 THEORETICAL ASPECTS OF IRREVERSIBILITY

Although the questions raised in this paper have been the subject of considerable interest and debate, not a great deal has been written on the subject. The terms "asymmetry" and "irreversibility" are often used in this context, although definitions vary. Sweeney and Fenichel (1987) differentiate between non-linearities and asymmetries in demand relationships. According to their definition, the demand relationship is symmetrical if the demand response to a price change is identically reversed as prices return to their initial levels, so that even non-linear demand functions can be symmetric. Wirl (1988) equates asymmetrical and non-linear demand functions, but states that the asymmetry of the demand relation itself is insufficient to explain the weak response of energy demand to recent price falls, and looks further to factors that alter parameters of the demand function itself or affect the dynamic aspects. Watkins and Waverman (1987) define symmetry in the same way as Sweeney and Fenichel, so that all static demand curves are symmetric, but go on to discuss how symmetric price changes can have irreversible effects when demand curves shift.

A number of attempts at empirical investigation of the question also exist, but the problem is sometimes poorly defined and the tests employed not necessarily relevant, so that the results have often been inconclusive. The empirical evidence in many studies does support some sort of irreversibility or structural change in energy demand relationships when estimated over long observation periods. Other authors, for example, Mossavar-Rahmani, Hogan, Jorgenson and Cooper (1988) find that models with large long-run elasticities and slow adjustment processes give consistent results for data covering long periods of time, including the first half of the 1980s. Clearly the evidence is contradictory.

Because of the lack of clarity over the issues involved, and the resulting confusion over how to formulate and test the relevant hypotheses, a necessary point of departure for this study is to define and clarify the concepts involved.

First, it may be useful to distinguish between the terms "asymmetry" and "irreversibility". As it will be used in this study, "symmetry" will denote similarity on either side of an axis or, in two dimensions, a point. In the context of demand/price relationships, it can be defined in terms of the demand response to equivalent upward and downward price movements from a given price. Energy demand is thus defined to be "symmetric" at P_0 if, for a given Δ, a change in price from P_0 to $P_0 + \Delta$ results in an equal but opposite change in demand as does a price change from P_0 to $P_0 - \Delta$. Thus, the demand response is "asymmetric" at P_0 if a given price increase results in a decrease in demand that is either larger or smaller than the increase resulting from an equivalent price fall.

Defined in this way, "symmetry" has nothing to do with whether demand reverts back to *initial* levels following a return to *initial* prices. Instead, this is a question of "reversibility". We define energy demand to be "reversible" with respect to price changes if the *magnitude* of the demand response resulting from a change in price from P_0 to $P_0 + \Delta$ is exactly opposite that resulting from a price change from $P_0 + \Delta$ to P_0. If this is the case, demand will return to its initial level, as prices do. On the other hand, if demand does not return to its initial level, we can say that an "irreversible" change in demand has occurred.

In order to understand how these concepts can be applied to energy demand, we must be able to specify the mechanics of the process governing the relationship between energy prices and energy demand. Clearly, this relationship cannot be viewed as static. The arguments for the non-instantaneous adjustment of energy demand are obvious and have been discussed at length in many articles on energy, so need not be enumerated here. The primary justification has to do with the relationship between energy and capital equipment and the adjustment costs, time-lags, etc. that affect investment decisions. Energy consumption at any point in time is largely given by the characteristics of the current stock of capital, which in turn have been determined not only by present energy prices, but also by past ones, as well as by past and present expectations regarding future prices. In such a dynamic world, the response of energy demand to a given price change will be distributed over time, only to reach equilibrium or steady state after all desirable adjustments have been made. Therefore, in the analysis of energy demand it is necessary to distinguish between the *dynamics*, i.e. the nature and speed of the intertemporal adjustment process, and the *steady-state* or long-run characteristics. Any asymmetries or irreversibilities in energy demand will also have to be analysed in this context.

We will begin with the easiest to conceptualize: the long-run equilibrium relationship. For the moment we will assume that that such a relationship exists and that it is static (unchanging). Further, we will only concern ourselves with price changes, and therefore assume that all other long-run demand determinants (e.g. income) remain constant.

For any normal good, we can envision a downward-sloping demand curve that relates quantity demanded to price. At any given price, the demand curve is symmetric at P_0, i.e. the absolute values of the changes in demand are equal for equal price increases and decreases of any magnitude, only if the demand curve is *linear* (or linear in the price interval in question). All *non-linear* demand curves, on the other hand, imply asymmetric responses for *all* but infinitessimal price changes. (This is irrespective of the symmetry inherent in the point elasticities, which are by definition strictly valid only as the price change approaches zero. Clearly in this case, the magnitude of the price change must be taken into account.) For any well-behaved demand curve that is continuous and non-increasing in prices, as the price change increases in magnitude the "asymmetry" of the demand response will necessarily become more pronounced. Whether upward price movements will have a larger or smaller effect on demand than equivalent downward price movements will depend on the characteristics of the particular non-linear function in question. For a constant elasticity (double-logarithmic) demand function, for example, price increases will have a smaller effect on demand than equivalent price decreases, given the same initial price. Furthermore, the extent of the asymmetry increases with the size of the price change and with the slope of the curve (i.e. its point elasticity). The characteristic of constant elasticity ensures, however, that an identical asymmetrical relationship holds around all points on the demand curve (i.e. for all price and demand levels).

Clearly, the asymmetry of the long-run demand curve arises purely as a result of non-linearities. The same is not true, however, regarding irreversibility. In fact, the entire concept of the static demand curve is meaningless without the characteristic of reversibility, since unless the demand curve shifts an increase in price followed by a decrease back to its initial level must *always* result in demand returning to its original level. In a purely static world, adjustment from one equilibrium to another is instantaneous so that shifts cannot occur and demand responses must *ceteris paribus* be reversible. Whether or not the elasticities vary along the demand curve is irrelevant. Thus movements along any static demand curve are reversible, even if the demand response is not symmetric in the sense defined above.

The notion of irreversibility, then, is incompatible with movements along a static demand curve, but instead presupposes some sort of shift or tilt in the demand curve itself. However, once we allow the demand curve to shift, some notion of time must enter the analysis. Although we are still considering only long-run relationships, any change in the demand curve must occur at a particular instant in time or demanded from $Q_0(0)$ to $Q_1(0)$, while at the same time the shift in the demand curve leads to a further decline in demand to $Q_1(1)$. Now if the price reverts to P_0 at $t = 2$, the movement will be along demand curve D(1), so that demand will rise to $Q_0(2)$, which is lower than $Q_0(0)$. Thus demand will not be reversible, despite the fact that the curvature of the demand curve has not changed.

If the shift in the demand curve is not price related, the slope of the demand curve, and hence the price elasticity, is the same as previously, and the only change in the demand function is a decrease in the intercept. Although it is clear that irreversibilities can be caused by exogenous technical change, the notion of a once-and-for-all shift in the demand curve occurring at some instant in time is somewhat unrealistic. Although specific innovations may occur at individual points in time, innovations are being introduced continually, so that the effects of these on aggregate demand occur slowly over time, leading to a continual movement of the demand curve, instead of a once-and-for-all shift. There would thus be a series of demand curves D(t) each relating to a particular time, t. A similar continual downward shift of the demand curve could also arise as the result of a change in the composition of output, for example from heavy industries to services. In either case, if the changes are independent of prices, price elasticities remain unchanged.

Of course, technical progress could affect the curvature of the demand curve as well. An example would be the introduction of a new technology that allowed a greater degree of substitution between competing goods, for instance, oil and gas. The slope of the demand curves for both oil and gas would increase in this case, as would the price elasticities. Any asymmetries would again be solely the result of non-linearities. The question of irreversibility is somewhat more difficult to analyse, however, as it depends on the nature of the change in the demand curve. Since it is possible that the new demand curve intersects the old, the effects on demand of a price change from the point of their over a specified period, so that one demand curve pre-dates the other.

The simplest example of this is a once-and-for-all shift in the long-run demand curve. For example, the introduction of a new energy-saving technology would lead to a downward shift in the demand curve, so that at all price levels demand would be lower than previously. Such improvements in energy efficiency can be either independent of prices (exogenous technical change) or the direct result of energy price increases (price-induced technical change). As discussed above, in either case, the technological improvements may be permanent.

We will assume to begin with that the curvature of the demand curves before and after the shift is identical. Such a shift of the demand curve from D(0) to D(1) is illustrated in Figure 1. Since one demand curve pre-dates the other, the numbers in parentheses denote time t. A price rise from P_0 at $t = 0$ to P_1 at $t = 1$ would lead to a fall in the quantity

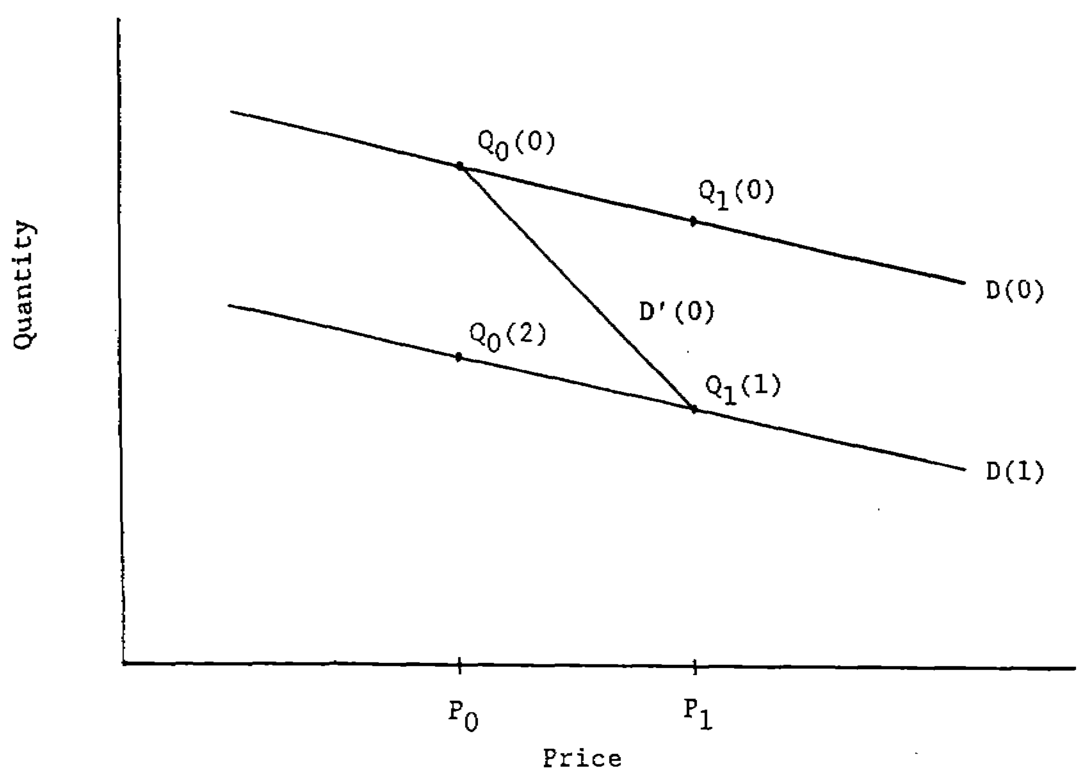

Figure 1: Irreversibilities caused by a Shift in the Demand Curve.

intersection will be reversible. In all other cases, however, demand will *not* be reversible. In the more general case of a downward shift combined with a change in slope, again irreversibilities will occur.

If the shift in the demand curve arises as the result of the price increase from P_0 to P_1 itself, we can think of demand moving directly from $Q_0(0)$ to $Q_1(1)$ down curve D'(0). The demand curve, as seen from the initial position (P_0, Q_0) at time t, can be represented by the kinked demand curve comprised of D(0) for prices below P_0 and D'(0) for price rises above P_0. This demand curve is clearly asymmetric at (P_0, Q_0) to falling and rising prices, but demand will still be reversible. The permanence, or irreversibility, of the price effect necessitates the movement of the demand curve to D(1).

Thus far we have assumed that only one particular price increase at a given time $t = 1$ permanently shifts the long-run demand curve down, so that demand moves along D(1) for all subsequent price changes. More particularly, this implies that further price increases do not affect the position of the "new" demand curve, so that D(1) holds for all time $t > 1$. Thus demand will be reversible for all future price changes, but it will *not* revert, however, to the demand-price relationships prevailing before the price rise at time $t = 1$.

This notion of irreversibility can be generalized by assuming that the slope of the demand curve is different for *all* price increases than it is for *all* price falls at *all* points in time - the jagged ratchet model proposed by Wolffram (1971). Since the same asymmetric relationship is assumed to hold for any price level at any given time, instead of having a single demand curve defining unique price-demand relationships, we have at each initial price level a kinked demand curve, which relates demand to rising and falling prices. The long-run level of demand is therefore not unique for any given price, but is instead a function of the entire past price history, so that a price rise/fall followed by an equivalent price fall/rise will not restore demand to its initial level. More specifically, if demand is more sensitive (elastic) to price increases than to price decreases, any periods of rising prices will result in permanent demand reductions, which will not be reversed as prices fall again to their initial levels.

The interpretation of this specification is illustrated in Figure 2. From the initial equilibrium, at price P_0 and demand $Q_0(0)$, a rise in price to P_1 at $t = 1$ would cause demand to fall according to demand curve $D_R(0)$ reaching equilibrium at $Q_1(1)$. For an equivalent price fall, to P_1', demand would follow curve $D_F(0)$ to $Q_1'(1)$. Since the slope of D_R is greater than that of D_F, $|Q_1(1) - Q_0(0)|$ is greater than $|Q_1'(1) - Q_0(0)|$, and the elasticity for rising prices is greater than that for falling prices. If the price falls again in time $t = 2$ from P_1 back to P_0, demand will move along $D_F(1)$, with the same slope as $D_F(0)$, to $Q_0(2)$, which is less than $Q_0(1)$, so that a period of rising prices followed by a

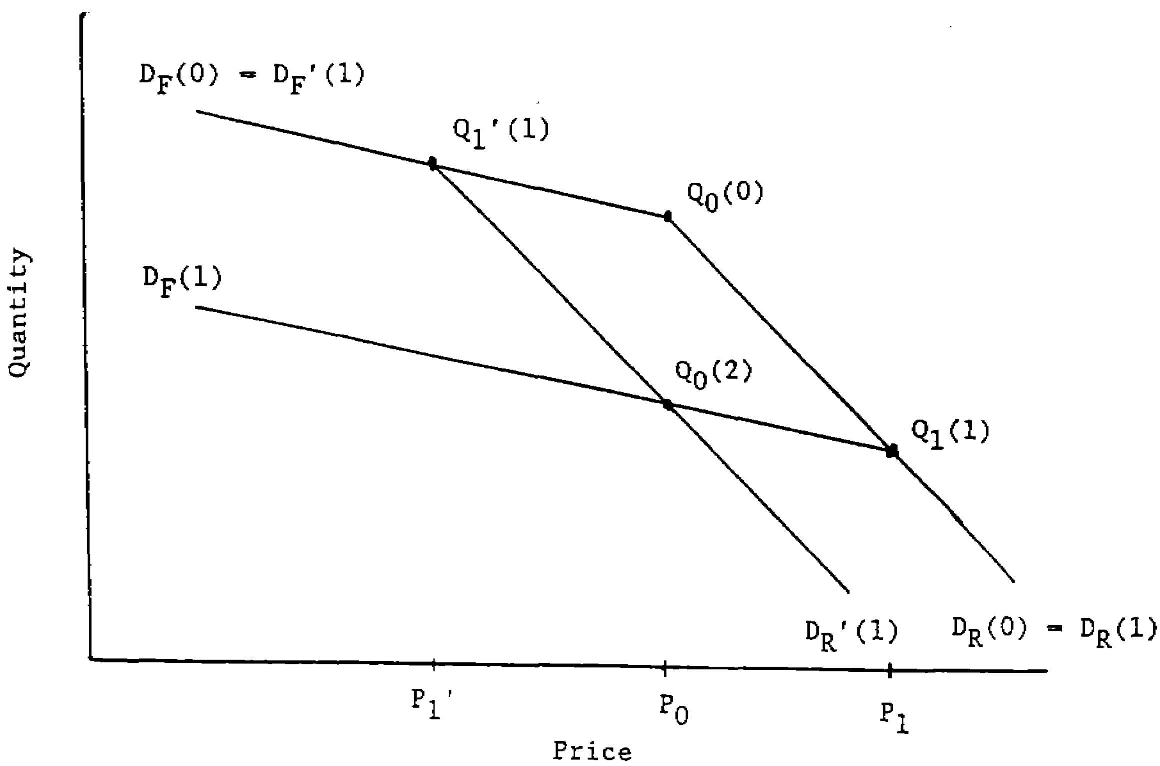

Figure 2: Irreversibilities caused by Asymmetry of Price Responses: Jagged Ratchet Model.

period of falling prices will not restore demand to its initial level and demand will be irreversible. By the same reasoning, a rise in prices from P_1' back to P_0 in time $t = 2$ will result in demand $Q_0(2)$, the same level as if the price rise had pre-dated the price fall. Again, demand is not restored to its initial level $Q_0(0)$. Demand is thus not only asymmetric to rising/falling prices, but also irreversible.

It is apparent from Figure 2 that, if demand is more elastic to rising than to falling prices, the slope of D_R will be greater than the slope of D_F, so that greater price variability will lead to lower final levels of demand, given identical initial and final prices. This seems quite reasonable since price variability can be seen as a measure of uncertainty, and the more uncertain consumers are concerning prices, the more likely they will be to decrease their dependency on energy consumption, or their reliance on a particular energy source.

We can also extend the reasoning behind Figure 1 to derive another irreversible specification based on the notion of asymmetric price responses, but with slightly different assumptions. Instead of allowing *all* price rises to have a different effect on demand than price falls, we assume that only price rises *above some given level* result in irreversibilities. One possible assumption is that only price rises above all previous prices, that is above the previous maximum, give rise to irreversibilities. These assumptions result in the ratchet model of Traill, Colman and Young (1978).

The situation is illustrated in Figure 3. Starting at the initial price P_0 and demand $Q_0(0)$, a price fall at $t = 1$, say to P_1, causes demand to move along $D(0)$ to $Q_1(1)$. For all subsequent price rises (or falls) that result in price levels less than or equal to $P_m = P_0$, the previous maximum price, demand follows curve $D(0)$, so that a return to P_0 will restore demand to its initial level $Q_0(0)$. As long as prices do not rise above the maximum P_0, demand will be symmetric to price rises and falls and thus reversible. However, if the price

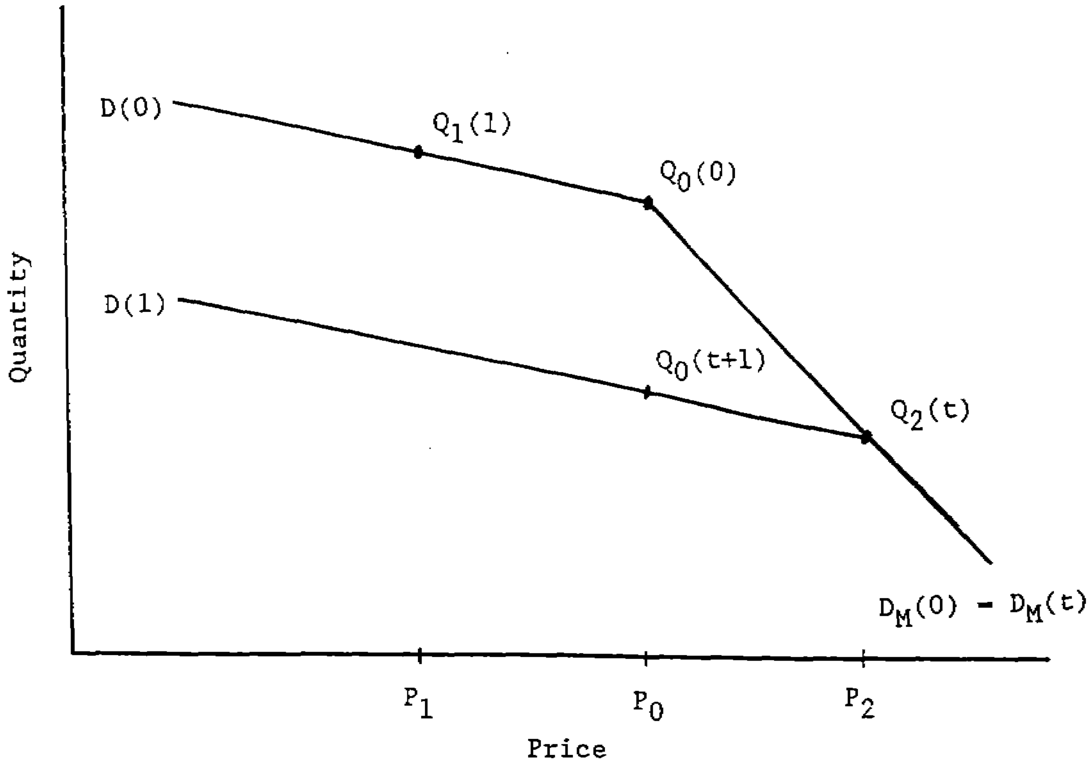

Figure 3: Irreversibilities caused by Asymmetry of Price Responses: Ratchet Model.

rises above all previous prices, so that $P > P_m = P_0$, demand will move along $D_M(0)$, which has a greater slope than D(0), implying a greater price elasticity. Thus a price rise to P_2 at time $t > 0$ will result in a demand of $Q_2(t)$. If the price falls again, demand moves along D(1), with the same slope as D(0), so that a fall to P_0 will increase demand to $Q_0(t+1)$ which is lower than $Q_0(0)$, so that demand does not return to its previous level and the effect of the price rise is therefore irreversible. For all subsequent price rises or falls, demand moves along D(1), until the new maximum price $P_m = P_2$ is surpassed and demand declines along $D_M(0)$ once again. In this case, asymmetries, and hence irreversibilities, only arise when prices surpass all earlier prices.

The basic difference between the situations illustrated in Figures 2 and 3 is that in Figure 2 the asymmetric demand curve denoted by D_FD_R can be thought to "move" for every price change, so that the relationship implied holds for all initial prices, whereas in Figure 3, on the other hand, $D_F D_R$ only "moves" when prices rise above their previous maximum levels, so that the asymmetry implied only holds for such price increases. Also, as seen in Figure 3, if prices rise only once above their previous maximum, this would be equivalent to a once-and-for-all downward shift in the demand curve and the situation would revert to that described in Figure 1.

Clearly, price-induced changes in the demand relationship as described in Figures 1-3 can be brought about by factors other than permanent improvements in energy efficiency. For example, if energy prices rise more in one country than in others, energy-intensive industries in that country will become less competitive, resulting in a change in the composition of production from heavy energy-intensive industries to low-energy high-tech industries or services. As prices fall, this change is unlikely to be reversed. Other examples are changes in behavioural patterns on the part of consumers or changes in government policy relating to regulations on fuel efficiency standards which initially may have been directly influenced by price considerations or awareness. If these changes become permanent, the implications for the reversibility of demand will be the same as outlined above. As we have seen, as price returns to its original level, demand will not return to its previous steady state, but will remain on a lower level.

Thus far we have limited the discussion to the irreversibility of *long-run* demand. As was pointed out earlier, the *dynamics* of the adjustment process to long-run equilibrium are also of utmost importance in analysing energy demand. The characteristics of the long-run demand relationship - and any asymmetries or irreversibilities that may exist - will determine energy demand in the long run after complete adjustment to a given price change. But the length of time required for that adjustment, and its distribution over time, are represented by the dynamics of the adjustment process.

Using our earlier definitions of symmetry and reversibility, we can see how these apply to the dynamics of energy demand in relation to price changes. If, at a given demand-price equilibrium, equal price increases and decreases produce equal but opposite intertemporal demand changes and achieve equilibrium in the same time, the adjustment process is symmetric. Clearly this requires that long-run demand is itself symmetric. If, on the other hand, the intertemporal response pattern and speed of adjustment differ, there may be said to be dynamic asymmetries in the reaction to price changes, even if long-run demand is itself symmetric. Such dynamic asymmetries occur, for example, if there is a generally slower or delayed adjustment to price decreases as compared with price rises. One possible reason for this is that price rises may lead to an earlier retirement of energy-inefficient capital, whereas price decreases will not necessarily lead to an earlier replacement of efficient capital. Dynamic asymmetries may also be accounted for by differences in expectations. Consumers may believe price rises to be permanent and thus react immediately, but believe price falls to be temporary and because of this respond only after the lower price has been maintained for some period of time. In the long run, however, the total response is the same for both price increases and decreases.

In terms of the dynamic demand relationship, if the adjustment mechanism is independent of the direction of the change in price, the response will be symmetric. This is the normal assumption made in energy demand models. In order to allow for dynamic asymmetries, the adjustment process itself must be allowed to vary according to the direction of the price change.

Similarly, the *reversibility* of the dynamic adjustment process can be defined in terms of the concepts used earlier. The dynamic process of energy demand is reversible if for a price change from $P_0 + \Delta$ to P_0 the duration of adjustment to equilibrium is identical to and the path followed an exact reversion of that for a change in price from P_0 to $P_0 + \Delta$.

Clearly, if long-run irreversibilities exist, demand must also be irreversible in the dynamic sense, since the former requires a change in the steady state to which the process is moving. The converse, however, does not hold. Since the path of the dynamic adjustment process can be independent of the characteristics of the long-run demand function, reversible long-run relationships can be reached through either reversible or irreversible adjustment processes.

It is clear that dynamic asymmetries will result in an irreversible adjustment path. However, even if the dynamic adjustment process is symmetric at all price levels, it will not be reversible unless the adjustment path is linear. Since demand will generally be irreversible in the dynamic sense, it is the asymmetry of the dynamic adjustment process that will be of most relevance in explaining the recent sluggishness in energy demand.

There are basically three cases to be considered. If energy demand is totally reversible in the long run, the intertemporal path of adjustment could be symmetric or asymmetric to rising and falling prices. In both cases a return to pre-1974 energy prices will lead to a reversion of demand to its earlier levels in the long run. With a symmetric path of adjustment, the distribution over time of the response and the total speed of adjustment will be identical for rising and falling prices. On the other hand, if demand is asymmetric in the dynamic sense, the demand response to price increases will be smaller (larger) in the short and medium term than those experienced in conjunction with price falls and the speed of adjustment will be slower (faster). Finally, if long-run irreversibilities exist, demand behaviour in both the short and the long run will be different from that of the 1970s, as will the time required for complete adjustment.

3 THE MODEL

3.1 Long-run Energy Demand

Empirical analysis of energy demand necessitates the formulation of an economic model from which the relationship between energy demand and its determining factors can be derived. The model employed here is a simple, reduced form most often employed in aggregate energy demand studies, which relates energy demand primarily to its price and some measure of income or output. Although various functional forms could be specified, the double-logarithmic is chosen. The long-run demand function for energy is thus:

$$E^{*} = \alpha + \beta P + \phi Y \qquad (1)$$

where E^{*}, P and Y are the natural logarithms of the quantity of energy consumed, the real price of energy and real income or output.

Although the model is extremely simplified, it can be derived from the traditional assumptions of cost minimization on the part of firms and utility maximization on the part of households. For firms, the specification of a CES production function and simplifying assumptions regarding the prices of capital and labour allow energy demand to be modelled solely as a function of the price of energy and output.[1] The use of a more generalized production function without simplifying assumptions concerning the prices of other inputs would clearly give a more realistic representation of the technology. Such an approach would result, however, in a system of interrelated demand equations that would make the modelling of irreversibilities far more difficult and in

[1] See Nordhaus (1977) for such a derivation.

practice limit the possibility of allowing for a generalized dynamic adjustment process. Although the model employed has obvious shortcomings, it allows the analysis of irreversibilities within a generalized dynamic framework.

For the household sector the specification given in (1) requires far less restrictive assumptions. Given that households maximize their utility by allocating their consumption between energy and non-energy goods, the demand for energy becomes a function of the price of energy in relation to other goods and real income.

Finally, by assuming that real income and output are related to real GDP, Y in (1) can be replaced by real GDP. Also, as much of energy consumption is obviously dependent on climatic factors, a degree day variable, DD, is included in (1) when appropriate. Finally, when the model is employed for a particular energy form, for example, oil, the real prices of substitutes, P_s, for s = g, e and c for gas, electricity and coal, are also included in (1).

The simplifying assumptions made in equation (1) provide us with a fairly simple demand model which ought to provide a reasonable approximation at the aggregate level. However, we might expect the production model to perform more poorly at a more disaggregate level, for example in explaining industrial energy demand.

3.2 The Specification of Irreversibility

In the models described above, long-run energy demand is assumed to be perfectly reversible to any changes in the exogenous variables. They must therefore be extended to allow for the existence of long-run irreversibilities and/or dynamic asymmetries or irreversibilities of the nature discussed in Section 2. As discussed there, long-run irreversibility requires the demand function itself to be a function of time or price history. Two of the irreversible specifications employed in the empirical study involve generating new variables that allow such a dependency, and including these variables in the estimated demand functions. Both of these are based on the assumption of asymmetric price responses, which cause shifts in the long-run demand curve.

The first specification is based on the reasoning in Figure 2 and thus distinguishes between rising and falling prices generally, by allowing the slope of the demand curve, and hence the price elasticities, to be different for price increases and price decreases. The new variable generated, P+, is defined as the sum of all price rises from time s = 0 (the initial year of the data sample) to time s = t:[2]

$$P+(t) = \sum_{s=0}^{t} [(P(s) - P(s-1)] \text{ for } P(s) > P(s-1). \qquad (2)$$

A similar variable, P-, can be constructed for falling prices. By including P+ and P- in the demand function in the place of P, the elasticity for rising prices is determined by the coefficient of P+ and the elasticity for falling prices by the coefficient of P-. Of course, the coefficients of both P+ and P- should be negative, and if the coefficient of P+ is greater (smaller) in absolute value that that of P- demand is more (less) elastic to rising than to falling prices.

It can easily be shown that including both P+ and P- in the demand equation is equivalent to including only P+ along with the actual price variable, P. The elasticity for rising prices is determined by the sum of the coefficients of the two price variables, while the effect of price falls is determined solely by the coefficient of the actual price variable. If the coefficient of P+ is not significantly different from zero, the elasticities for falling and rising prices will be identical so that demand will be reversible. If P+ is significant, however, the price effects will not be symmetric and demand will be irreversible. Again we would expect the coefficient of P+ to be negative, implying that demand is more elastic to price rises than to price falls. However, even the opposite situation would imply irreversibility, although it

[2] A derivation of this can be found in Houck (1977).

would be far less realistic since it would imply that the demand curve was shifting *upwards*, and that greater price variability would lead to higher levels of demand.

The second specification derives from the notion of irreversibility depicted in Figure 3, by allowing only price rises above the previous maximum price to have asymmetric effects. This specification is formulated by generating a new variable P_m, defined as the maximum previous price:[3]

$$P_m(0) = P(0)$$
$$P_m(t) = P(t) \text{ if } P(t) > P(t-i) \text{ for all } i = 1, \ldots, t \quad (3)$$
$$P_m(t) = P_m(t-1) \text{ otherwise,}$$

where P denotes the real price of energy and t represents time. The variable P_m is then included in the demand equation along with the actual price P.

By this definition, price rises above the previous maximum will cause a shift in the long-run demand curve, represented by the coefficient of P_m, which we would expect to be negative. In terms of price elasticities, if both P_m and P are significant, the price elasticity for a price fall will be determined simply by the coefficient of P. The relevant elasticity for price rises will be either the coefficient of P (if the price does not rise above its previous maximum) or the sum of the coefficients of P and P_m (if a new maximum is reached). If only P_m is significant, price decreases have no effect on demand, nor do price increases below the previous maximum, and the coefficient of P_m determines the price elasticity when prices rise above all previous levels. In both of these cases, demand is *not* reversible. However, if the coefficient of P_m is insignificant, all price changes have symmetric effects so the demand curve does not shift and demand will be reversible.

By including both P+ and P_m in the demand function along with P, we can distinguish between the effects of price rises

[3] See Traill, Colman and Young (1978).

both below and above the previous maximum as well as of falls. In this case, the long-run demand function in (1) becomes:

$$E^{*} = \alpha + \beta_P P + \beta_+ P+ + \beta_m P_m + \phi Y. \qquad (4)$$

The elasticity pertaining to price falls is obtained from the coefficient of P, β_P, the elasticity for price rises below the previous maximum from $\beta_P + \beta_+$, and for price rises above the previous maximum from $\beta_P + \beta_+ + \beta_m$. If either β_m or β_+ equals zero, the model results in one of the above irreversible specifications. Of course, if both β_m and β_+ equal zero we revert to the symmetric, reversible model.

The final specification includes the introduction of a simple time trend into the reversible demand function. A trend can be interpreted as a continual shift in the long-run demand function that occurs as a result of technical change or some other exogenous factor. In the case of technical change, we would expect a downward shift in the demand curve, so that the coefficient of the time trend would be negative. As discussed in Section 2 above, such a shift in the demand curve would cause demand to be lower at all price levels, so that although the price effects may be symmetric, demand would not be restored to previous levels despite a return to initial prices. Although the shift is not price related, and the use of a trend highly simplistic, its significance would indicate an irreversibility of demand. Of course, a time trend can also be combined with the asymmetric price response specifications described above.

3.3 Dynamic Specification

The model described above pertains to long-run demand relationships. Adjustment to long-run equilibrium is, however, certainly not instantaneous, so that some sort of dynamic adjustment mechanism must be included in the model specification if this is to be estimated on the basis of time-series data. Since we have no a priori justification for choosing a particular dynamic specification - for example, the declining geometric lag scheme implied by the partial adjustment model - a reasonable way of proceeding would be to begin with a very general formulation, and simplify this on the basis of the information contained in the data itself and on the realism of the resulting estimates - the general-to-specific methodology of model reduction suggested by Hendry (1989). The generalized dynamic specification is of the form:

$$\Phi(L)E_t = \alpha_0 + \beta(L)P_t + \phi(L)Y_t \qquad (5)$$

where L is the lag operator such that for any variable X:

$$\begin{aligned} L^r X_t &= X_{t-r} \\ \beta(L) &= \beta_0 + \beta_1 L + \beta_2 L^2 + \ldots + \beta_n L^n \\ \phi(L) &= \phi_0 + \phi_1 L + \phi_2 L^2 + \ldots + \phi_n L^n \\ \Phi(L) &= 1 - \Phi_1 L - \Phi_2 L^2 - \ldots - \Phi_n L^n \end{aligned} \qquad (6)$$

where n is the total lag length. The parameters of the long-run demand function given in (1) can be obtained as follows:

$$\begin{aligned} \alpha &= \alpha_0/\Phi(L) \\ \beta &= \beta(L)/\Phi(L) \\ \phi &= \phi(L)/\Phi(L). \end{aligned} \qquad (7)$$

The estimated equation could thus be written as:

$$E_t = \alpha_0 + \sum_{i=0}^{n_p} \beta_i P_{t-i} + \sum_{i=0}^{n_y} \phi_i Y_{t-i} + \sum_{i=1}^{n_e} \Phi_i E_{t-i} \qquad (8)$$

where n_p, n_y and n_e define the lengths of the lags for the respective variables. We see that the partial adjustment model is a special case of this general dynamic specification, since if $n_p = 0$, $n_y = 0$ and $n_e = 1$, we have:

$$E_t = k + \beta_0 P_t + \phi_0 Y_t + \Phi_1 E_{t-1}. \qquad (9)$$

The partial adjustment form can thus be tested against the more general specification (8) by testing the significance of the contribution of the additional lagged terms.

Equation (8) can be rewritten with the dependent variable in differenced form so that the change in energy consumption becomes a function of current and lagged changes in prices and income, the lagged levels of these variables and lagged changes and levels of energy consumption:

$$E_t = \alpha_0 + (\sum_{i=0}^{n_p} \beta_i)P_{t-1} + (\sum_{i=0}^{n_y} \phi_i)Y_{t-1} + (\sum_{i=0}^{n_e} \Phi_i - 1)E_{t-1}$$

$$+ \beta_0 \Delta P_t + \phi_0 \Delta Y_t - \sum_{i=0}^{n_p} \sum_{j=i+1}^{n_p} \beta_j P_{t-i-1} - \sum_{i=0}^{n_y} \sum_{j=i+2}^{n_y} \phi_j Y_{t-i-1}$$

$$- \sum_{i=0}^{n_e} \sum_{j=i+2}^{n_e} \Phi_j E_{t-i-1}. \qquad (10)$$

One advantage of this formulation is that the estimated coefficients are easier to interpret. The long-run solution is obtained from the coefficients of the level variables, as is shown by equations (7). The first four terms on the right-hand side can thus be rewritten as $(1 - \Sigma\Phi_i)$ times the deviation from long-run equilibrium, which can be interpreted as an error correction mechanism.[4] The short-run, or immediate effects of changes in the exogenous variables are given by the coefficients of the differenced variables, β_0 and ϕ_0.

There are numerous advantages to allowing for a general dynamic structure in the empirical analysis of the reversibility of energy demand. First, if the dynamics of the adjustment process are misspecified, the estimates based on the model may be biased, and we may mistake this misspecification for structural instability, and hence as an indication of irreversibility. A further advantage of a more

[4] See Davidson, Hendry, Srba and Yeo (1978) or Hendry (1980) for a discussion of error correction models.

general lag structure is that it permits the possibility of dynamic asymmetries and irreversibilities to be investigated. Since the intertemporal adjustment process is not constrained to be identical for all exogenous variables, the effects of price increases and decreases need not be distributed identically over time. The initial response of one or the other can be delayed, and the speed of adjustment to equilibrium can differ.

As a starting-point for the estimation, lags on all price variables and income as well as energy consumption were included as independent variables. The sample size - 29 annual observations - and the number of exogenous variables included in the general specifications limit the maximum lag to two years. Although this restricts the dynamic structure, it does permit some flexibility, particularly since the adjustment process is not constrained to be the same for all explanatory variables.

From this unrestricted dynamic specification, the model is sequentially simplified by omitting those lagged variables that have a statistically insignificant influence. In order to determine the final dynamic specification, this process is repeated until further deletions are rejected on the basis of statistical tests. Both F-tests for the restrictions imposed and the Schwarz criterion (SC) are reported. Since the partial adjustment model is nested within the unrestricted model, it can be easily tested against the more general dynamic specification.

Choice of the final model cannot however, be based solely on statistical significance tests and other criteria must be employed in evaluating alternative models. Most obviously, the estimated parameters should be economically acceptable; particularly, own-price elasticities should be negative and income elasticities non-negative. In addition to this, the validity of the statistical assumptions of the estimation process should be examined. Most importantly, the disturbance term should have zero mean and be serially independent. In order to test for autocorrelation of the residuals the Lagrange multiplier (LM) test is employed, which unlike the Durbin-Watson statistic is applicable when lagged dependent variables are included among the regressors. Tests are made for serial correlation up to the third order, denoted LM(3). Only these are reported in the tables unless significant first- or second-order correlation is detected.

In order to investigate the possibility of non-zero disturbance means, the functional form of the model is tested against one that includes the square of the fitted dependent variable as a regressor (the RESET-$\hat{Y}^2$ test). Finally, the estimated parameters of the model should be constant over the observation period, so that no unexplained structural change is evident. The stability of the estimated equations over the observation period is analysed by recursive estimation techniques and the appropriate Chow-tests.[5]

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[5] All estimations and statistical tests were carried out using the program package *PC-GIVE*. The reference manual, Hendry (1989), can be consulted for the statistical formulation of the tests used and further references concerning these.

4 ENERGY CONSUMPTION AND PRICES IN THE UK: 1960-88

The model described above was estimated for energy demand in the UK on the basis of annual data covering the period from 1960 to 1988. Besides total final energy consumption, separate analyses were carried out for total final oil consumption, energy and oil demand in the domestic and industrial sectors and oil demand for road transport. Before commencing with the presentation and discussion of the empirical results, it is worth taking a look at the development of energy consumption and energy prices in the UK over the period concerned. Besides presenting a description of the statistical data that serve as basis for the econometric analysis, the historical overview will provide a clear picture of the specific UK energy situation, which will be valuable for the interpretation of the results obtained.

4.1 Data Sources and Definitions

The analysis of total energy and oil demand concerns *final* consumption. Total energy demand is thus defined as the use of petroleum products, electricity, gas, coal and other solid fuels by industry, transport, and other final consumers. It does not include energy used by energy production industries and losses in conversion and distribution. Total final oil demand relates to the same consumer categories and thus specifically excludes oil used in electricity generation.

Data on the consumption of oil, coal, gas and electricity in the above-mentioned sectors were obtained from the Department of Energy's *Digest of United Kingdom Energy Statistics*. Average retail prices for the individual energy products - light fuel oil, heavy fuel oil, gasoline, diesel oil, coal, gas and electricity - for industry and households were taken from OECD *Energy Prices and Taxes* for the years

1978-88. For earlier years, data from the US EIA publication *International Energy Prices* were used, along with UK sources, after being adjusted to be consistent with the OECD data. All price data are inclusive of taxes. Private consumption and Gross Domestic Product in constant prices as well as the consumer price index and GDP deflator were taken from the International Monetary Fund's *International Financial Statistics*, updated with UK statistical sources. Degree day data were provided by the Department of Energy.

Prices and quantities for energy aggregates were computed using a discrete Törnquist approximation to a Divisia index, instead of the Btu weighting method most often used in energy demand studies.[6] Thus, the price index for aggregate energy is computed as a cost share (s_i) weighted average of the changes in the prices (P_i) of the n energy products that make up the aggregate according to:

$$\text{Ln } P_t = \text{Ln } P_{t-1} + \sum_{i=1}^{n} [(s_{i,t} + s_{i,t-1})/2][\text{Ln } P_{i,t} - \text{Ln } P_{i,t-1}]. \tag{11}$$

Similarly the quantity of aggregate energy is obtained by weighting the quantities of the individual energy products by their prices, instead of by their thermal content. In this way, energy is aggregated in the manner of other economic goods. Unlike Btu aggregation, the Divisia method does not impose a priori the perfect substitutability of all energy forms that make up the aggregate in order to be consistent with optimizing behaviour on the part of energy consumers. Another advantage of this approach is that it allows for the possibility that differences in Btu prices among energy products reflect qualitative differences, as is clearly the case with oil and coal, for example. Of course, the price and quantity series obtained will differ depending on the method of aggregation as will the estimated elasticities, so that one

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[6] For a discussion of the problems of using Btu aggregation and the advantages of the Törnquist index see Berndt (1978).

should be aware of this when comparing the results of different studies.[7]

4.2 Historical Overview

As the study is concerned with various aggregates of energy or oil demand, the relevant energy and oil prices are aggregates of the prices of individual energy forms and/or oil products. Since oil is an element of all aggregates considered and since changes in world oil prices have been the motive force behind the energy developments of the past fifteen years, oil prices are a natural point of departure. In order to put energy price developments in the UK into the context of world oil prices we will begin by looking at the two oil price shocks of the 1970s and the price collapse of 1986 and their impact on the prices of individual oil products on the UK market.

The tripling of crude oil prices on world markets in 1974 was clearly felt by the UK market. Prices of oil products to UK consumers did not rise in anything like the same proportion, however, and there were considerable disparities in the actual price increases among individual petroleum products. Heavy fuel oil for industrial consumers experienced the greatest price rise of all products - about 140 per cent - while the price of light fuel oils rose about 90 per cent. The prices of motor gasoline and automotive diesel were not affected so greatly, since maximum retail prices were imposed during the period from 15 December 1973 to 20 December 1974, which held the price increase down to only around 20 per cent. With the lifting of the price controls, the prices of motor gasoline and automotive diesel rose by around 70 per cent and by 40 per cent respectively in 1975. In the same year, the prices of heavy and light fuel oils increased further by 24 and 36 per cent respectively. The differences in the overall price increases during 1974 and

[7] Nguyen (1987) estimates US energy demand using both Btu and Divisia aggregation and finds that the long-run price and income elasticities are greater when Divisia aggregation is used.

1975 among products are explained partly by the varying roles of transportation and distribution costs and by differential taxation rates.

With the second oil price shock in 1979 world crude prices more than doubled on spot markets. The price rise was, however, not immediately transmitted to consumer markets. During 1979 crude oil import prices for the UK in pounds sterling rose by only around 20 per cent, the brunt of the effect occurring in the following year when prices surged by another 55 per cent.[8] Again the prices of the individual products on the UK market did not behave identically, with increases of between 25 and 30 per cent in 1979 and between 18 and 45 per cent in 1980. As with crude import prices, the prices of fuel oils increased more in 1980 than in 1979, while the reverse was true for motor fuels.

The oil price collapse of 1986 witnessed a fall in the price of Brent on the Rotterdam market by nearly 50 per cent. The fall in UK import prices in US dollars was the same, while in pounds the decrease was 55 per cent, the difference here being due to the weakening of the dollar. Again consumer prices in the UK did not fall proportionately. Heavy fuel oil fell by 53 per cent, light fuel oil by about 35 per cent and gasoline and diesel by only about 15 per cent. The reasons for the discrepancies amongst products are basically the same as those which explained the differences in the price rises of 1974-5.

In real terms, the price increases of the 1970s were somewhat smaller, as the general level of inflation in the UK was particularly high during the 1970s and early 1980s. The development of real oil prices to final consumers in the UK is shown in Figure 4. In all cases, the prices refer to some oil aggregate composed of various oil products. For industry the products concerned are primarily heavy and light fuel oils,

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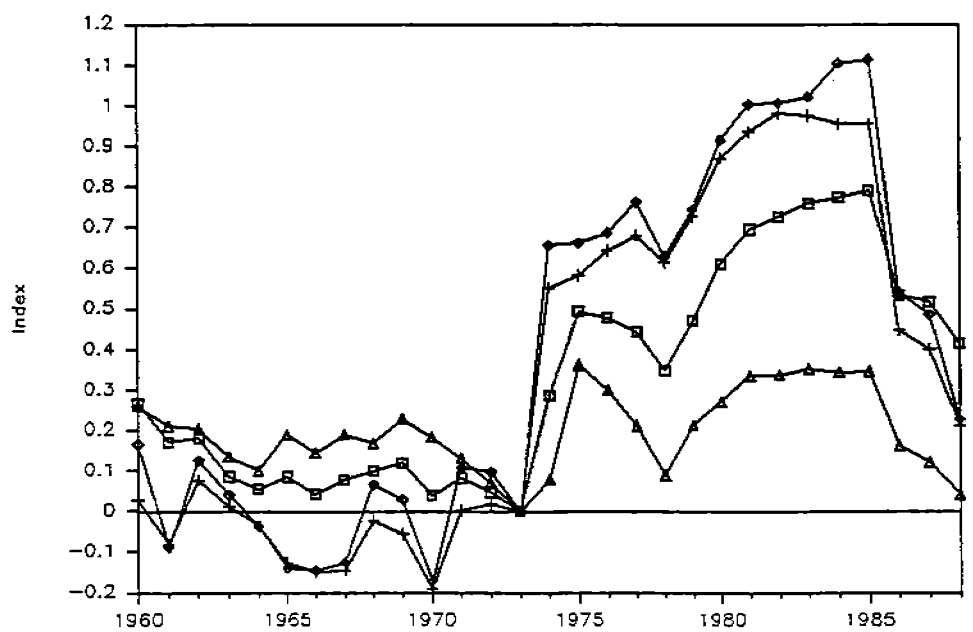
8 The price increase in US dollars was somewhat greater, owing to a decline in the dollar against European currencies from 1978 to 1980.

for the domestic sector light fuel oil only and for road transport motor gasoline and automotive diesel. The total price index includes all three of these sectors plus the commercial, public and agricultural sectors and other (non-road) transport. Again it should be stressed that we are concerned with the oil prices paid by *final consumers*, so that oil prices for electricity generation and prices of crude oil to refineries are *not* included. For the same reason, all prices include energy taxes and non-refundable VAT.

We see that for all sectors real prices fluctuated within a band of ±30 per cent in the 1960s, and that real prices were somewhat lower in 1973 than they were in 1960. The oil price shock of 1974 had the greatest impact on the industrial sector, with nearly a doubling of prices, primarily because heavy oil products, which experienced the greatest individual price rise, dominated. The smallest impact was felt by road transport, because of the price controls mentioned earlier, although in 1975 prices increased by more



□ Total ◇ Industrial + Domestic Δ Transport

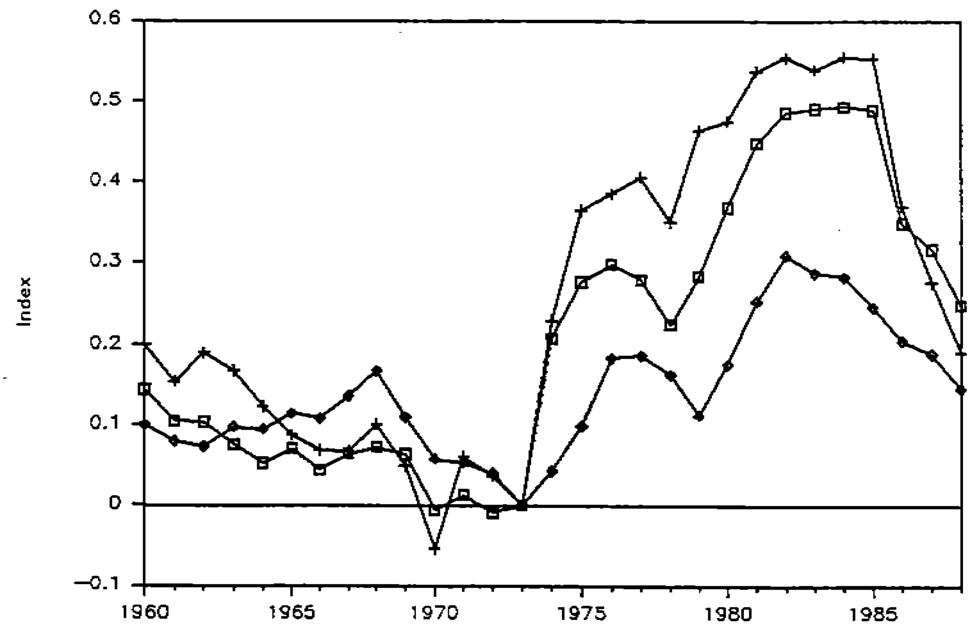
Figure 4: Logarithmic Index of UK Real Oil Prices (1973 = 0). 1960-88.

than 40 per cent. Given the price increases for the various sectors, the aggregate oil price rose by about 30 per cent in 1974 and 25 per cent in 1975.

For the three years following the price shock, oil prices continued to rise in the domestic and industrial sectors, but began to fall in 1976 in the transport sector. By 1978 all prices had fallen. The 1979 price shock increased all prices by about 15 per cent in real terms, although, in general, real prices were still below the highs reached during the previous few years. In 1980, however, real prices in both the industrial and domestic sectors increased by another 20 per cent, thus surpassing the price levels of the 1970s even in real terms, and prices continued to rise up until 1985. For road transport, we find, however, that although real prices rose between 1978 and 1981, they never quite reached the levels of the mid-1970s.

The price collapse of 1986 clearly reduced real oil prices for all sectors. The most substantial reductions occurred for industrial and domestic consumers, with real price decreases of 45 and 40 per cent respectively. For road transport, oil prices fell by about 16 per cent. In absolute terms, the real price falls of 1986 were only marginally smaller than the increases of 1974. Prices continued to decline over the next few years so that by 1988 real oil prices in both the industrial and domestic sectors were below those of 1974, and those for road transport had returned to pre-1974 levels. The aggregate price index for total final oil consumption does not show a similar decline, however, since the product composition of oil consumption had changed considerably over the intervening period, towards more highly refined and dearer products. In 1973, fuel oils comprised around 36 per cent of total final oil consumption, while in 1988 the share was less than 10 per cent. During the same period motor gasoline increased its share from 30 to over 50 per cent.

The development of aggregate *energy* prices over the past three decades is shown in Figure 5.[9] We see that the overall pattern has been broadly similar to that noted for oil. There are, however, some significant differences. First, there was an obvious decline in energy prices during the 1960s, as real electricity and gas prices fell more significantly than did oil prices. Secondly, aggregate energy prices did not rise as substantially in the 1970s or fall as drastically in the late 1980s as did oil prices.



□ Total + Industrial ◊ Domestic

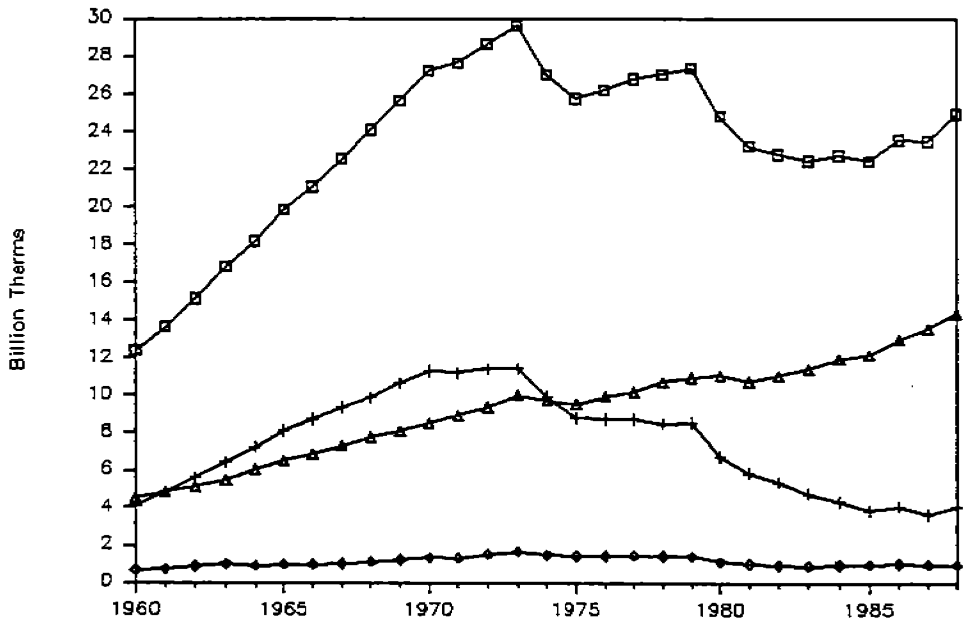
Figure 5: Logarithmic Index of UK Real Energy Prices (1973 = 0). 1960-88.

[9] The aggregate energy prices are calculated as Divisia indices as described in Section 4.1.

The next two figures show the development of final oil and energy consumption in the UK measured in thermal units. In Figure 6, we see that total oil consumption rose dramatically up until 1973, with the industrial and transport sectors accounting for most of the increase. Consumption fell in 1974-5, and then again 1980-81, in all sectors.

In industry, demand fell most substantially and continued to do so well into the 1980s. For the transport sector, demand continued to increase for most of the post-1975 period, although remaining below its previous trend. Finally, we see that the domestic sector accounts for only a small proportion of oil consumption, since more than 94 per cent of its energy needs are provided by other energy sources.

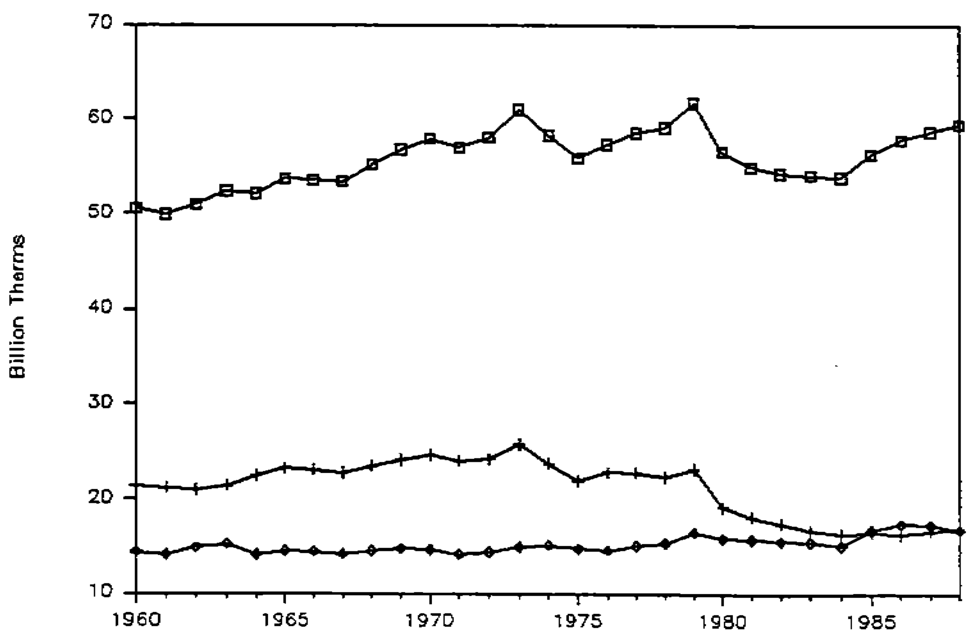
Figure 7 shows final energy consumption in the industrial and domestic sectors as well as totally. As was the case with oil consumption, total energy demand rose up until 1973, then fell considerably in 1974-5 and in 1980, although the changes have been somewhat less dramatic. Industrial energy demand displays a similar pattern. After 1984, however, total energy demand began to increase again, while industrial consumption remained more-or-less constant. By 1988 total consumption had nearly returned to its 1974 level, whereas industrial consumption was 30 per cent lower than it was in 1973 and even 20 per cent lower than it was in 1960. Consumption in the domestic sector was higher in 1988, however, than at any time previously.



□ Total + Industrial ◊ Domestic Δ Transport

Figure 6: UK Final Oil Consumption.

1960-88.



□ Total + Industrial ◊ Domestic

Figure 7: UK Final Energy Consumption.

1960-88.

5 THE EMPIRICAL RESULTS

In the following, we will begin with a presentation and discussion of the empirical results obtained for total final energy and oil consumption, and then go on to the results for the sectoral aggregates. Since none of the estimated models for energy and oil demand in the *industrial* sector could be accepted on the basis of the criteria outlined in Section 3.3 above, the results are not presented here and no conclusions can be drawn concerning irreversibility for that sector. Obviously, the simplifying assumptions made in the model formulation do not provide an adequate description of aggregate industrial energy demand and a more realistic model is needed. One of the major problems is the changing composition of industry over this period, which cannot be accounted for in the aggregate model.

5.1 Total Final Energy and Oil Demand

(a) Aggregate Energy Demand. The initial estimates were of the model shown in equation (8), including P+ and P_m as well as actual prices P along with GDP and a degree day variable DD, with lags of up to two years for all variables other than DD. Beginning with this specification variables were deleted on the basis of the tests outlined in Section 3.3 above. In the final specification all the price variables were statistically significant, but the total long-run effects were found to be insignificant. An explanation for this is the high degree of collinearity between P+ and Pm, which arises because the majority of price rises were in fact above the previous maximum price, so that P+ and P_m are nearly equivalent. As a result of this collinearity, the standard errors of these two variables are very large and their

long-run effects poorly determined. The long-run price elasticities based on this model are -0.04 for price falls, -0.86 for price rises and -1.28 for price rises above the previous maximum. However, the long-run effects of P+ and P_m are statistically different from zero only at the 15 per cent error level, while the effects of P are not significant even at much higher error levels.

The analysis was continued by considering P+ and P_m separately. The results are presented in Tables 1 and 2. In both cases the initial specification included two lags on all variables, but the second lag on the price and consumption variables and all lagged income variables were found to be non-significant, resulting in the specifications shown. Looking at the results for model A in both tables, we find that the inclusion of either P_m or P+ results in significant coefficients for both current and lagged values of P_m and the current levels of P+, but in both cases the coefficients of the actual price variables are insignificant, which implies that demand does not respond to falling prices. Excluding the lagged price variables (model B in each table) is rejected by the Schwarz criterion (SC) and F-tests and the current actual price variable is still not significant. Deleting the actual price variables results in models C(+) and C(m), both of which are accepted on the basis of the SC and F-tests. Further, we see that the LM tests reject residual autocorrelation and that the RESET tests for adding $\hat{Y}^2$ or t do not suggest functional misspecification nor the significance of a time trend. The recursive Chow-tests, shown in Figures A1 and A2 in the appendix for models C(+) and C(m) respectively, do not indicate any significant instability over the observation period. Particularly, we see that the Chow-tests for the 1986-8 period do not reject parameter constancy for years following the price collapse for either model.

Of the two price rise variables, P_m is found to have slightly more explanatory power than P+, so that the estimated standard errors are lower for the models containing the former variable. On this basis, the model including P_m is the

Table 1. Total Final Energy Demand: Estimated Models. All Models with Energy Consumption as the Dependent Variable.

	A(+)	B(+)	C(+)	D
k	0.49 (0.82)[1]	1.45 (2.42)	0.75 (1.28)	1.31 (2.86)
E(t-1)	0.79 (12.12)	0.67 (11.99)	0.83 (13.89)	0.86 (6.89)
Y	0.47 (3.42)	0.63 (4.86)	0.31 (3.54)	0.12 (1.42)
P	0.06 (0.54)	0.16 (1.48)		-0.32 (4.42)
P(t-1)	0.13 (0.98)			0.19 (2.14)
P+	-0.50 (3.36)	-0.41 (3.29)	-0.47 (5.82)	
P+(t-1)	0.11 (0.63)		0.29 (3.14)	
DD	0.11 (1.68)	0.95 (1.29)	0.12 (1.95)	0.10 (1.25)
R^2	0.99	0.99	0.99	0.99
DW	2.76	2.00	2.61	2.15
s	0.0149	0.0173	0.0150	0.0193
RSS	0.00420	0.00632	0.00475	0.00786
SC	-7.793	-7.628	-7.914	-7.410
LM(3)	1.83 F(3,16)[2]	0.90 F(3,18)	1.12 F(3,18)	0.79 F(3,18)
F-test for parameter restrictions:				
Model A to		4.80 F(2,19)**[3]	1.24 F(2,19)	8.28 F(2,19)**
RESET-$\hat{Y}^2$			0.28 F(1,20)	1.63 F(1,20)
RESET-t			0.48 F(1,20)	4.53 F(1,20)**

Price Elasticity	A(+) P+	A(+) P-	B(+) P+	B(+) P-	C(+) P+	C(+) P-	D P
Short-run	-0.44	(0.06)[4]	-0.25	(0.16)	-0.47	0	-0.32
Long-run	-0.95	(0.90)	-0.75	(0.48)	-1.06	0	-0.93

Income Elasticity	A(+)	B(+)	C(+)	D
Short-run	0.47	0.63	0.31	(0.12)
Long-run	2.24	1.91	1.82	(0.86)

Notes: 1. t-values.
2. Distribution and degrees of freedom for test statistics.
3. * and ** denote that test statistics are significant at the 95 and 99 per cent confidence levels respectively.
4. Elasticities in parentheses are based on non-significant parameter estimates.

Table 2. Total Final Energy Demand: Estimated Models. All Models with Energy Consumption as the Dependent Variable.

	A(m)	B(m)	C(m)	E
k	1.06 (1.32)[1]	3.26 (4.08)	0.81 (1.23)	-0.53 (0.47)
E(t-1)	0.86 (8.24)	0.58 (5.98)	0.90 (11.48)	0.82 (11.86)
Y	0.20 (1.26)	0.56 (3.69)	0.13 (1.15)	0.62 (2.50)
P	-0.07 (1.02)	0.01 (0.07)		-0.26 (3.71)
P(t-1)	0.12 (1.47)			0.25 (2.87)
P_m	-0.89 (5.26)	-0.43 (2.28)	-0.99 (7.80)	
P_m(t-1)	0.63 (2.64)		0.86 (4.94)	
DD	0.09 (1.44)	0.04 (0.53)	0.11 (1.94)	0.08 (1.08)
Time				-0.01 (2.13)
R^2	0.99	0.99	0.99	0.99
DW	2.41	1.70	2.32	2.27
s	0.0129	0.0191	0.0130	0.0179
RSS	0.00316	0.00767	0.00355	0.00640
SC	-8.077	-7.433	-8.204	-7.492
LM(3)	0.92 F(3,16)[2]	1.26 F(3,18)	1.39 F(3,18)	0.17 F(3,18)
F-test for parameter restrictions:				
Model A to		13.55 F(2,19)**[3]	1.17 F(2,19)	13.95 F(2,19)**
RESET-$\hat{Y}^2$			0.97 F(1,20)	1.11 F(1,20)
RESET-t			0.01 F(1,20)	

Price Elasticity	P_m	P	P_m	P	P_m	P	P
Short-run	-0.96	(-0.07)[4]	-0.42	(0.01)	-0.99	0	-0.26
Long-run	-1.50	(0.35)	-1.00	(0.02)	-1.30	0	-0.06

Income Elasticity	A(m)	B(m)	C(m)	E
Short-run	0.20	0.56	(0.13)	0.62
Long-run	1.42	1.33	(1.30)	3.44

Notes: 1. t-values.
2. Distribution and degrees of freedom for test statistics.
3. * and ** denote that test statistics are significant at the 95 and 99 per cent confidence levels respectively.
4. Elasticities in parentheses are based on non-significant parameter estimates.

preferred one. Although this suggests that price rises below the previous maximum price have no effect on demand, there are so few observations of such price rises that it may be unjustified to draw this conclusion. What is apparent, however, is that price falls have had a significantly smaller effect.

As the final models are expressed with the level of energy consumption as the dependent variable, the short-run elasticities are given by the coefficients of the current variables. We find that the immediate response to P_m is greater than that to P+, but the difference becomes negligible when the lagged price variables are excluded (model B), and the speed of adjustment increases. The positive coefficients of the lagged price variables indicate an overshooting of the price reaction, thus rejecting the validity of the partial adjustment model. The long-run price elasticities for the respective price rises, shown at the bottom of the tables, are on average around -1.0, and are generally greater for the models including P_m than for those including P+. The profile of the dynamic demand response to price increases also differs between the two models, with median lags of about two years for C(+) and one year for C(m).[10] However, in both models 90 per cent of the total response to price increases is completed in around ten years. Also, in both cases, the results suggest that demand does not react to price falls, implying total irreversibility.

All models indicate that the income elasticity is less than unity in the short run while the long-run elasticities are 1.3 and 1.8 in the P_m and P+ models respectively. The coefficient of the income variable is very small and not significantly different from zero in the model containing P_m (C(m)), but eliminating the lagged price term (model B(m)) increases its value and significance. Since the adjustment parameter also increases, the long-run elasticities are about the same.

[10] The median lag is the time required for 50 per cent of the total long-run adjustment to be completed.

Deletion of both P_m and P+ (model D in Table 1) increases the standard error markedly and is rejected on the basis of the SC and F-tests. Although this model results in estimates that are acceptable according to economic theory and is not rejected on the basis of the LM and RESET-$\hat{Y}^2$ tests, a RESET test for omitted variables rejects the model for one including a time trend at the 1 per cent error level. Furthermore, the recursive Chow-tests shown in Figure A3 in the appendix indicate that the model is unstable over the observation period. Particularly, the tests suggest a structural break around 1974[11] and parameter instability in 1978, 1980 and 1986. Allowing for differential intercepts and price coefficients for various sub-periods firmly indicates a reduction in the intercept term for the post-1973 period, suggesting a downward shift in the demand curve. The evidence for differential price effects between these two periods is less strong, however, so that constancy cannot be rejected.

Inclusion of a time trend in the reversible specification (model E in Table 2) reduces the standard error significantly, but it is still far above that of either model C(+) or C(m). As shown by the recursive Chow-tests in Figure A4 in the appendix, the stability of the parameter estimates improves, although the structural break in 1974 remains. However, parameter constancy between the 1962-73 and 1974-88 sub-periods cannot be rejected on the basis of the F-test since F = 2.46 with F(7, 13).[12] We find that the inclusion of the time trend indicates an energy-saving technical change of 1 per cent per annum, while at the same time reducing the long-run price elasticity to -0.06 and increasing the long-run income elasticity to an unrealistic 3.4. Although the models including P_m or P+ are still preferred, the significance of

[11] The F-statistic obtained by separately estimating the 1962-73 and 1974-88 periods is 3.21 with F(6, 15).

[12] The Chow-test used in the figures is not equivalent to the F-test obtained by fitting the model separately to the individual sub-periods, and when the forecast period of the Chow-test exceeds the estimation period, the F-test is preferred. In this case 1974-88 is larger than 1962-73, so the F-test given in the text should be used.

the time trend in the otherwise reversible model indicates a downward shift of the demand curve over time, which gives further support for the irreversibility of energy demand.

In order to compare the results obtained with those of other studies, is helpful to begin with the reversible specifications. Considering other studies for the UK, both the estimated price and income elasticities based on model D are greater than those obtained by Kouris (1980) or Mittelstadt (1983), who report long-run income elasticities of 0.4 and 0.6 respectively and a price elasticity of -0.4. The long-run price elasticity is also greater than that estimated by the Department of Energy (1989) of -0.2. However, all of these studies are based on a considerably shorter observation period - from 1960 up until 1978 (1980 for the DOE) - so that their ability to capture the long-run response to the price shocks of the 1970s is questionable.

Our estimates do agree rather better with those based on more recent data. Welsch (1989), for example, considers various model specifications for eight countries both individually and pooled for the period 1970-84, and finds that the long-run price elasticities range from -0.1 to -0.9 and the income elasticities from 0.7 to 2.3 in the individual countries. His average results for the UK, based on three preferred model specifications, indicate a price elasticity of -0.1 in both the short and long run, and income elasticities of 0.5 and 0.7 in the short and long run respectively. In all of the models for the UK, the significance of a time trend cannot be rejected, so the estimates Welsch presents are based only on models including the time trend. The significance of the time trend agrees with our own results, as does the long-run price elasticity based on the comparable model (E).[13]

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[13] The significance of a time trend in explaining aggregate energy demand is also supported by Beenstock and Willcocks (1981) in their study of energy consumption in industrialized countries for the period 1950-78. Using an error correction methodology and reversible specification, they find a long-run price elasticity of -0.06. These results are not totally comparable with those in the text, however, since world oil

However, our income elasticity is much higher, which is probably explained by our inclusion of pre-1970 data. The significance of the time trend can be interpreted as evidence of autonomous energy-saving technical progress, which again supports the irreversibility of energy demand. However, as our own results have shown, this irreversibility is better explained - in a statistical sense - in terms of asymmetric price effects.

A few studies that specifically test for structural change in the aggregate energy demand relation can be found in the literature. Prosser (1985) investigates trends in elasticities for final energy demand over the period 1960-82 in the seven largest OECD countries by means of moving regressions and Chow-tests. From the moving regressions, there is some indication that the elasticities are not constant over the period, and a Chow-test for pre- and post-1970 data indicates structural change. In a more recent study, Paga and Brennard (1989) examine changes in energy intensity in groupings of OECD countries for the period 1960-88. Using a Chow-test for 1986-8 versus the earlier part of the period, they find a significant change only for Western Europe. They report short-run price elasticities of -0.2 for 1960-85 and 0 for 1986-8, and conclude that at least short-run energy demand in Western Europe is asymmetric in its response to energy price movements.

In summary, although it may be difficult to choose unequivocally between the various models estimated in our study, the significance of P_m, P+ and the time trend in the different models and the instability of the reversible specification are clearly indicative of an irreversible decline in energy demand over the period studied. This conclusion is also supported by many of the other studies mentioned above. Clearly, if demand were completely reversible to price changes, *ceteris paribus*, we would expect demand to be much higher than it is today, given that real

prices are used as the price variable instead of energy prices.

energy prices are far lower than they were in the early 1980s and real income considerably higher. The degree of long-run irreversibility is, however, more difficult to ascertain. Although the empirical results indicate that price decreases have had no effect on demand, implying complete irreversibility, this seems too strong a conclusion to make given the time-horizon considered. As of 1988, the 1986 price collapse did not appear to have had a significant impact on demand, the increase in consumption being totally explained by the growth in real GDP. However, it should be pointed out that the price of aggregate energy is still about 20 per cent higher in real terms than it was previous to the first oil price shock, so that further price falls may yet stimulate demand.

(b) Final Oil Demand. The initial model for total final oil consumption included both P_m and P+ as well as actual oil prices P, and the prices of gas, coal and electricity. Since the number of degrees of freedom was limited, it was necessary to limit the lags on each of the exogenous variables to one year. Current and lagged coal prices, the current prices of electricity and gas and the lagged income variable were all found to be statistically insignificant and were therefore excluded from the model. The resulting estimates, for the model written in differenced form as in equation (10), are shown as model A in Table 3. We see that the lagged levels of P+, Y and the prices of gas and electricity are of the expected sign and significantly different from zero, indicating a long-run relationship between these variables and oil demand. Neither the lagged actual oil price variable P, nor the lagged previous maximum P_m is found to have a significant influence, however, indicating that price decreases have no long-term effect on demand and that price rises above the previous maximum price have no greater long-run effect than general price increases. The insignificance of $\Delta P+$ and the significance of ΔP_m suggest that only price increases above the previous

Table 3. Total Final Oil Demand: Estimated Models. Models A-C in Differenced Form, with Change in Oil Consumption (ΔE) as Dependent Variable. Model D in Partial Adjustment Form, with Oil Consumption as Dependent Variable.

	A		B		C			D	
k	-1.18	(1.80)[1]	-1.17	(2.58)	0.22	(0.55)		0.15	(0.29)
E(t-1)	-0.24	(3.81)	-0.24	(5.48)	-0.08	(1.45)		0.87	(16.67)
ΔE(t-1)	-0.36	(2.70)	-0.36	(2.99)	-0.25	(1.37)			
Y(t-1)	0.71	(3.34)	0.71	(4.97)	0.11	(1.48)	[Y][5]	0.68	(4.58)
ΔP	-0.09	(1.46)	-0.09	(2.28)	-0.27	(6.34)			
P(t-1)	0.02	(0.31)	0.02	(0.36)	-0.25	(3.78)	[P]	-0.28	(6.71)
ΔP_m	-0.57	(3.38)	-0.58	(5.68)					
P_m(t-1)	0.02	(0.09)							
ΔP+	-0.00	(0.01)							
P+(t-1)	-0.38	(2.36)	-0.37	(4.53)					
P_g(t-1)	0.17	(1.75)	0.17	(2.76)	0.27	(2.65)	[P_g]	0.18	(1.73)
P_e(t-1)	0.16	(2.93)	0.16	(3.28)	0.15	(2.08)	[P_e]	0.15	(2.17)

	A	B	C	D
R^2	0.97	0.97	0.90	0.99
DW	2.03	2.04	2.31	1.99
s	0.0123	0.0116	0.0199	0.0222
RSS	0.00228	0.00229	0.00753	0.01035
SC	-7.931	-8.153	-7.208	-7.135
LM(3)	3.06 F(3,12)[2]	3.13 F(3,14)	1.17 F(3,16)	0.59 F(3,18)

F-test for parameter restrictions:

	A	B	C	D
Model A to		1.68 F(2,15)	8.63 F(4,15)**[3]	
Model B to			19.45 F(2,17)**	
Model D incl. P_m and P+				6.43 F(2,19)**
Model D incl. P_m				13.40 F(1,20)**
Model D incl. P+				10.26 F(1,20)**
RESET-$\hat{Y}^2$		1.29 F(1,16)		1.85 F(1,20)
RESET-t		0.99 F(1,16)		1.30 F(1,20)

	P-	P+	P_m	P
Own-price Elasticity				
Short-run	-0.09	-0.09	-0.68	-0.28
Long-run	0	-1.54	-1.54	-2.15
Income Elasticity				
Short run		0.71		0.23
Long run		2.95		1.77
Cross-price Elasticity: Gas				
Short-run		0.17		(0.18)[4]
Long-run		0.71		(1.38)
Cross-price Elasticity: Electricity				
Short-run		0.16		0.15
Long-run		0.66		1.15

Notes: 1-4 see Table 2.
5. Variables names in square brackets apply to model D.

maximum have a different short-term effect from price decreases.

Deleting the two variables with the lowest t-values, $P_m(t-1)$ and P+, results in model B. We see that the deletion of these variables is not rejected on the basis of the SC or the F-test, and that the residuals appear to be uncorrelated on the basis of the DW statistics and LM tests. The functional form of the model is not rejected by the RESET-$\hat{Y}^2$ test and the RESET test for omitted variables does not suggest adding a time trend. Finally, by the recursive Chow-tests shown in Figure A5 in the appendix, the estimated parameters appear to be stable over the observation period.

From the t-values of estimates, it is obvious that further reductions - with the exception of the elimination of the lagged oil price - would be rejected on the basis of significance tests. Since this has indeed been the case, and since the deletion of the lagged value of the actual oil price has no effect on the other estimated parameters, these results are not reported here. We see from the estimates of model C, however, that deletion of all P_m and P+ variables from model A - resulting in a reversible specification - is rejected at the 99 per cent confidence level on the basis of the F-tests, and that the coefficients of both E(t-1) and Y(t-1) are reduced to non-significance.

The estimates of the oil price parameters in the preferred model (B) imply that price decreases and increases below the previous maximum have equal short-run effects, with an elasticity of about -0.1, while the short-run response to price rises above the previous maximum is considerably greater, nearly -0.7. The response to P_m appears, however, to be a short-term over-reaction, as demand begins to be restored in the following years, and the long-term effect is equivalent to that of other price rises, with an elasticity of -1.5. The immediate demand increase in response to price falls also seems to be an over-reaction, as demand falls again over time and finally returns to its initial level.

Since the long-run effects of P+ and P_m on demand are identical, the difference between them lies solely in their dynamic adjustment profiles. Besides the obvious difference in the short-run impact noted above, the median lag for P_m (two years) is shorter than that for P+ (four years), so that the speed of adjustment to price rises above the previous maximum is somewhat faster than that for other price increases. The differences in the intertemporal demand response to these two types of price increases as well as to price falls are clearly illustrated in Figure 8.

As far as inter-fuel substitution is concerned, the coefficients of the prices of electricity and gas are significantly positive, indicating that these two energy sources are substitutes for oil. (Note that we are estimating *final*, not *primary*, oil demand.) The reaction is delayed, however, since only lagged, not current, prices have a significant influence, which is implicit in the lack of significance of the P_g and P_e variables. A long-run cross-price elasticity of around 0.7 is indicated for both of these alternative energy sources, and the intertemporal adjustment patterns are seen to be identical.

The estimated elasticities suggest that equal percentage increases in the prices of oil, gas and electricity would have a negligible long-term effect on oil demand. The converse does not hold, however: if all prices fall by 1 per cent, oil demand will fall by about 1.4 per cent as a result of the substitution response and the insensitivity of oil demand to decreases in its own price. This result must be treated with caution, of course, since no allowance was made in the model for irreversible asymmetric responses to the prices of competing energy forms.

The estimated income elasticity is 0.7 in the short run, and reaches nearly 3 in the long run. This unreasonably high value for the long-run income elasticity may challenge the actual values of the other estimated parameters, and perhaps may cause an over-estimation of the extent of irreversibility.

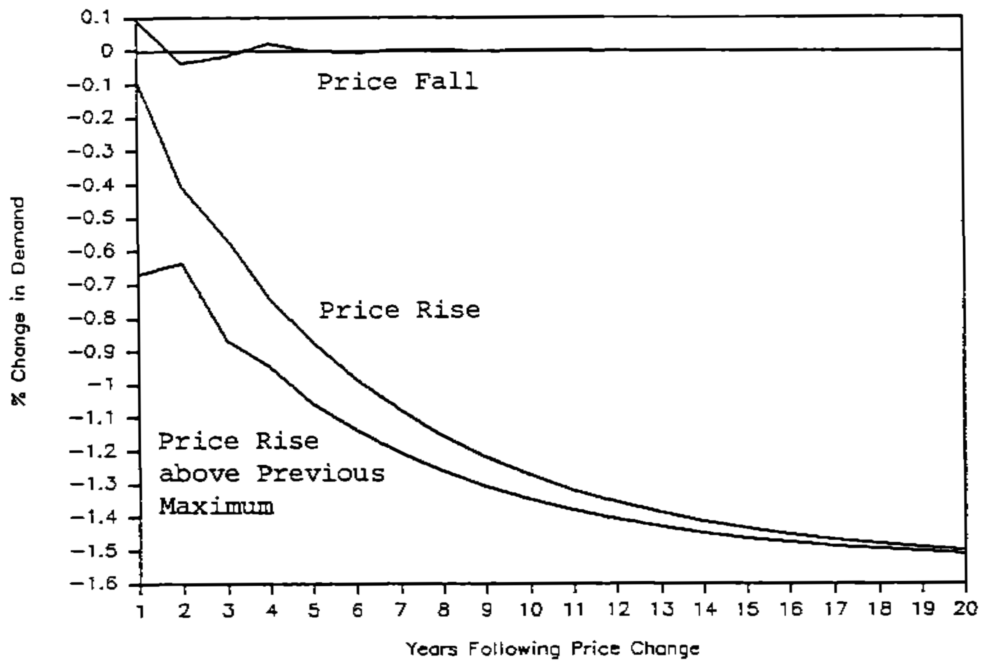

Figure 8: Intertemporal Response of Total Final Oil Demand to 1% Price Change.

However, in virtually all the specifications estimated, including a simple partial adjustment model with only income and actual prices as explanatory variables, the estimated long-run income elasticities were very near to or greater than 2. Only by excluding the prices of substitutes is the income elasticity reduced to a value of around unity. This model is found to be highly unstable over the observation period, however, and is rejected in favour of one including P+, which indicates a greater response to price increases than to price falls, thus again supporting the notion of irreversibility.

For purposes of comparison, the estimates of a simple partial adjustment model are also presented - model D in Table 3. We see that coefficients are of the expected sign and generally significant, and that the model is found to be acceptable on the basis of the LM tests for autocorrelation and the RESET tests. Furthermore, the estimates appear to be stable over the observation period. Particularly, the F-test for a structural break in 1974 results in a test statistic of

2.47 with F(6, 15) and the Chow-test for the years 1986-8 versus the pre-1986 period is 2.09 with F(3, 18), so parameter constancy is not rejected in either case.

Regarding the estimated elasticities for Model D given in Table 3, we find that the resulting own- and cross-price elasticities are rather suspiciously large. Also, considered together, the elasticities indicate that a 1 per cent increase in the prices of oil, gas and electricity would increase oil demand by about 0.4 per cent as a result of the substitution effect, which again seems rather doubtful.

Although, considered on its own, we have little cause to reject the reversible specification (model D), its performance should be compared with those of the irreversible models. Since it is not nested within any of the previous models, we cannot test it against these with the SC or F-test used in other cases. Instead, in order to test model D against the preferred model B, we test each separately against an unrestricted model which has as exogenous variables those included in both models B and D. We then test the restrictions implied by each of the models, that is, for each model encompassing their union. The resulting F-statistics are 1.41 F(3, 14) for model B and 9.76 F(7, 14) for model D. Thus on the basis of this test, model B is preferred. Further, we see from the results of the F-tests for model D, as presented in Table 3, that this model is rejected at the 99 per cent confidence level in favour of partial adjustment specifications including either P+, P_m or both.

Quite a few studies reported in the literature also test for the structural stability of oil demand relationships and differential price effects, although generally primary, not final, oil consumption is considered. Bopp (1984) in a study for the US finds no structural change between the pre- and post-embargo periods for total oil, but does find structural change for each oil product considered individually. He finds, however, that the period 1978-82 was significantly different from the past. Two other studies test for irreversible price responses using an model specification similar to our own. Bye (1987) in a study for Norway finds significant irreversible asymmetric price responses using a static model, but these are reduced to insignificance when lagged adjustment effects are included. In a study for various groups of OECD countries, however, Kouvaritakis (1987), finds that oil demand is more responsive to rising than to falling crude oil prices, and that the difference becomes more pronounced in the long run.

In summary, the empirical results for final oil demand provide strong evidence for the existence of irreversibilities. Although a reversible specification is found to be stable over the observation period, the irreversible model gives a far better explanation of the underlying data, as well as somewhat more reasonable elasticity estimates. There is a clear indication that oil demand has been more sensitive to rising than to falling prices, at least during the period considered. The results indicate that price falls - including those of the 1980s - have had only a small short-term impact on oil consumption, so that the demand reductions resulting from the price rises of the 1970s appear to be completely irreversible. Again, we must qualify this conclusion. Since prices have been low for only a relatively short period, if the response to price falls is for some reason considerably more delayed than the reaction to price rises, demand may yet begin to be reversed. Further, although aggregate real oil prices have plummeted since 1985, they are still well above their levels previous to the first oil price shock, so that further price declines can lead to significant demand increases.

5.2 The Transport Sector

The results for the estimation of the model for gasoline and diesel used for road transport are shown in Table 4. The results are presented for the specification in which the dependent variable is expressed in differenced form as in equation (10), so that the long-run effect of each exogenous

Table 4. Oil Demand for Road Transport: Estimated Models. All Models in Differenced Form, with Energy Consumption as Dependent Variable.

	A		B		C		D	
k	1.33	(1.41)[1]	0.43	(3.38)	0.40	(3.52)	0.57	(6.49)
E(t-1)	-0.10	(0.66)	-0.22	(3.23)	-0.23	(3.52)	-0.10	(2.07)
ΔY	0.60	(2.76)	0.73	(5.21)	0.66	(5.63)	0.61	(4.57)
Y(t-1)	-0.06	(0.14)	0.31	(2.34)	0.34	(2.68)	0.07	(0.90)
ΔP	-0.14	(1.36)	-0.06	(1.76)	-0.06	(1.74)	-0.11	(3.66)
P(t-1)	-0.11	(1.09)	-0.04	(1.11)	-0.02	(0.84)	-0.04	(1.22)
ΔP_m	-0.29	(0.79)	-0.48	(2.37)	-0.50	(2.64)		
P_m(t-1)	-0.39	(1.70)	-0.25	(1.70)	-0.32	(2.42)		
P+	0.07	(0.45)						
P+(t-1)	0.13	(0.96)						
ΔE(t-1)	-0.56	(2.95)	-0.58	(3.42)	-0.58	(3.99)	-0.41	(2.79)
ΔY(t-1)	1.14	(3.60)	0.90	(4.34)	0.87	(4.43)	0.93	(4.17)
ΔP(t-1)	0.00	(0.02)	0.04	(0.88)				
ΔP_m(t-1)	-0.05	(0.18)	-0.14	(0.90)				
ΔP+(t-1)	0.06	(0.42)						
D_{74}	-0.08	(5.29)	-0.08	(5.70)	-0.09	(6.34)	-0.08	(5.03)
R^2	0.96		0.95		0.95		0.93	
DW	2.37		2.16		2.06		1.88	
s	0.0095		0.0088		0.0085		0.0098	
RSS	0.00098		0.00109		0.00116		0.00173	
SC	-8.267		-8.533		-8.712		-8.558	
LM	1.19 F(1,10)[2]		0.69 F(3,11)		0.27 F(3,13)		0.78 F(3,15)	
F-test for parameter restrictions:								
Model A to			0.39 F(3,11)		0.40 F(5,11)		1.20 F(7,11)	
Model B to					0.47 F(2,14)		2.06 F(4,14)	
Model C to							3.52 F(2,16)	
RESET-$\hat{Y}^2$					1.30 F(1,15)		0.77 F(1,17)	
RESET-t					0.63 F(1,15)		4.75 F(1,17)**[3]	
Price Elasticity					P	P_m	P	
Short-run					-0.06	-0.56	-0.11	
Long-run					(-0.10)[4]	-1.50	(-0.40)	
Income Elasticity								
Short-run					0.66		0.61	
Long-run					1.49		(0.70)	

Notes: 1. t-values.
2. Distribution and degrees of freedom for test statistics.
3. * and ** denote that test statistics are significant at the 95 and 99 per cent confidence levels respectively.
4. Elasticities in parentheses are based on parameters that are not significantly different from zero at the 10 per cent error level.

variable can be calculated simply as the coefficient of the lagged level of that variable divided by the negative of the coefficient of the lagged level of the independent variable.

Model A is the unrestricted model, which includes P+ and P_m as well as P, with two lags on the dependent variable and on all exogenous variables, except for D_{74} which is a dummy variable to account for the effects of rationing during 1974. We find that most of the estimated coefficients, with the exception of those relating to P+, are of the correct sign. As might be expected, however, many of the estimated parameters are very poorly determined. All of the coefficients relating to P+ are very close to zero and have exceedingly low t-values, suggesting that we cannot distinguish between the effects of price falls and rises below the previous maximum price. As indicated by the magnitude of the coefficients and the t-values of the P_m variables, the probability is much greater that price rises above the previous maximum have had a greater effect than other price changes.

In model B, all P+ terms are deleted. We find that the estimated standard error decreases somewhat, and that the restrictions imposed are not rejected by either the SC or the F-test. The LM-test indicates that omitting P+ does not introduce autocorrelation. Most of the coefficients are now much better determined, and all except those of $\Delta P(t-1)$, $\Delta P_m(t-1)$ and $P(t-1)$ are significantly different from zero at error levels below 10 per cent. Deleting the lagged differences of P and P_m results in model C. The standard error continues to decrease so that the restrictions are not rejected by either the SC or the F-tests and the LM-test still does not suggest residual autocorrelation. All the estimated parameters are now highly significant, with the exception of the coefficient of $P(t-1)$. Although this suggests that price falls and rises below the previous maximum have no significant long-term influence on demand, the coefficient is of the correct sign, so it has not been excluded from the model. The additional tests of model C, reported at the bottom of the table, give us no cause to reject it. Particularly, we see that the inclusion of a time trend is not supported by the F-test and the functional form is not rejected by the RESET-test for including $\hat{Y}^2$. Finally, the Chow-tests shown in Figure A6 in the appendix indicate stability over the estimation period.

The final results reported, model D, are obtained by the further deletion of all P_m variables, resulting in a reversible model. We see that the standard error increases, as does the SC. Although the reductions are not rejected at the 5 per cent error level on the basis of the F-test, they are very nearly so. It can also be seen that the reversible specification is rejected on the basis of the RESET-test for adding a time trend. Further, it could be added that a Chow-test indicates a structural break occurring in 1975. Testing for the constancy of the individual coefficients over the observation period shows a decrease in the intercept term for the post-1974 period, suggesting a downward shift in the demand curve. This allowance for differential intercepts considerably reduces the long-run price elasticity, resulting in estimates very similar to those obtained for model C.

The reason for this is that the P_m variable is a step variable increasing only in 1975. All previous price rises left real price levels below that of 1960, and price increases after 1975 - including that of 1979 - did not bring real prices above those of 1975.[14] Since P_m rises only in 1975 and never falls, its effect is to shift the long-run demand curve downwards for the subsequent period. Including P_m is thus equivalent to allowing for differential intercepts in the reversible model for the pre- and post-1974 periods. In both cases, the results indicate a downward shift in the long-run demand curve for the post-1974 period of about 14 per cent. Model C, including P_m explains this shift in terms of the price shock, instead of as a change in some undefined

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[14] The oil price shock of 1974 did not have its full effect on consumer prices until the end of December, since maximum prices were imposed for most of the year (see Figure 4).

exogenous factor, as is the case of the model that is characterized by differential intercepts for the pre- and post-1974 periods. In either case, however, demand will not be reversible, unless there is an equivalent upward shift in the demand curve. On the basis of our data sample, there is no indication that such a shift has yet occurred.

The estimated elasticities are shown at the bottom of Table 4. For the reversible specification - model D - the estimated price elasticities are -0.1 and -0.4 in the short and long run respectively, although the long-run elasticity is not statistically significant. The irreversible specification - our preferred model, C - indicates, however, that price rises above the previous maximum have had considerably greater effects than other price rises or falls. This is better illustrated in Figure 9, which shows the profiles of the demand response over time to the various types of price change of 1 per cent. We see that demand has been rather insensitive to price falls and rises below the previous maximum. There appears to be a significant, but small, immediate impact, with an elasticity of -0.06. The effect diminishes somewhat in the following year, increasing rather rapidly over time to reach -0.10 in the long run. However, the long-run elasticity is not statistically significant, so we cannot reject the hypothesis that the long-term impact is in fact zero. The picture is very different when the price rises above its previous maximum level. The immediate effect is rather large, a reduction in demand of 0.56 per cent, but we see again that demand tends to overshoot somewhat initially. By the third year, the response becomes more pronounced again, to tail off more-or-less geometrically after about five years. In the long run, the effect is a decrease in demand of about 1.5 per cent.

Since the P_m variable only takes into account the price rises of 1975, the decrease in demand resulting from price increases above the previous maximum indicated by the model is purely the result of the first price shock. Specifically, we

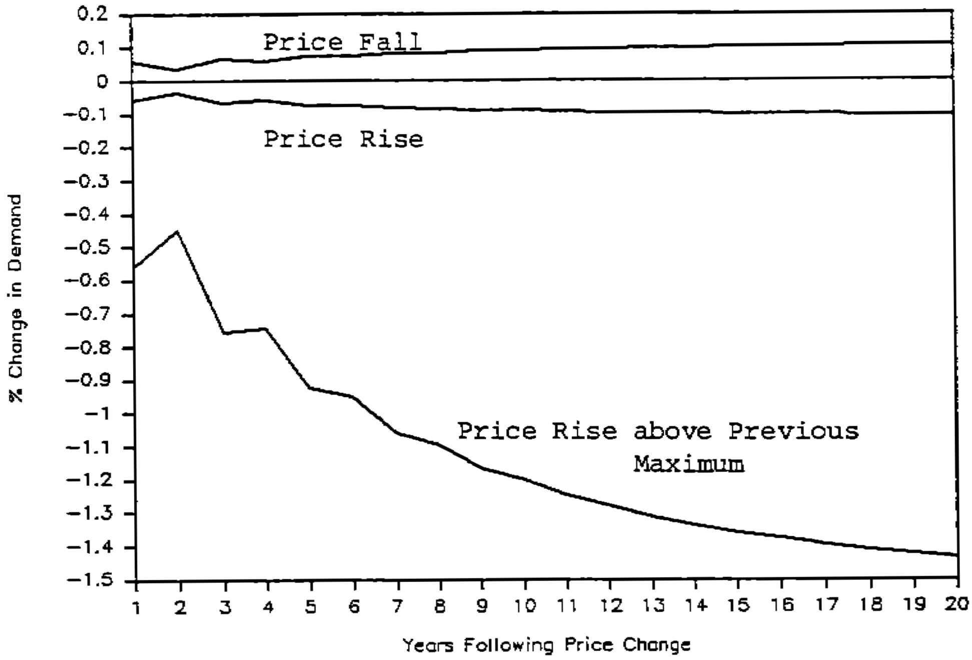

Figure 9: Intertemporal Response of Oil Demand in Road Transport to a 1% Price Change.

find that the price rises of 1974-5 have led to an irreversible decrease in demand of about 14 per cent in the long run. Thus if real prices return to their 1973 levels, *ceteris paribus*, demand will still be 14 per cent lower than it would have been if the initial price shock had not occurred.

We could also apply the estimates obtained for model C to calculate the effects of other price changes. In doing so we assume the elasticity for price falls and rises below the previous maximum to be -0.1 in the long run, even though this estimate was not found to be significantly different from zero in a statistical sense. The implication of our results is that, taken together, the irreversible and reversible effects of the 1974-5 price increases have led to a long-run decrease in demand of 16 per cent. The subsequent price falls during 1976-8 and price rises during 1979-83 more-or-less cancelled each other out, changing long-run demand by plus and minus 2 per cent respectively. Only about another 2 percentage points of the initial demand decrease was recaptured as a result of the price collapse of 1986-8, which returned real prices to very near their 1973 levels.

Given a non-zero elasticity relating to price falls, the irreversibility of demand to price changes does not mean, however, that the long-run demand losses caused by the 1974-5 price shock can not be recaptured, only that this would require prices to fall well below their pre-1974 levels. According to our model estimates, real prices would need to fall to about 20 per cent of what they are today, assuming an elasticity for price falls of -0.1. However, if demand is totally insensitive to price falls, so that the long-run elasticity is in fact zero, the demand loss will not be recaptured no matter how low prices fall.

Finally, the model indicates that the renewed growth in demand witnessed in the 1980s can largely be attributed to the renewed growth in real income. The estimated income elasticities are about 0.7 in the short run and 1.5 in the long run. We find too that the adjustment to changes in income is somewhat quicker than adjustment to price changes - 90 per cent of the total response to an income change occurs within seven years, while only about 70 per cent of the long-run response to price rises above the previous maximum is complete in this time. Thus, a partial adjustment model in which the speed of adjustment is the same for all exogenous variables would not be supported by the data.[15]

Although our results are based on models that are rather different from those used in the majority of empirical studies, a comparison with their estimates would be of interest. Most of the studies in the literature pertain to gasoline demand solely, however, so we would not necessarily expect complete agreement. In their survey of energy demand studies, Bohi and Zimmerman (1984) report "consensus" estimates of price elasticities for gasoline to be -0.2 in the

[15] The presence of residual autocorrelation found in the partial adjustment model can also be indicative of a misspecification of the dynamics of the adjustment process.

short run and -0.7 in the long run, while Dargay (1990) estimates average elasticities in the European OECD countries for the period 1960-85 of -0.3 and -0.9 for gasoline and -0.08 and -0.14 for automotive diesel. Both estimates for gasoline are rather higher than our estimates from the reversible model, D, of -0.1 and -0.4 in the short and long run respectively,[16] but some of this difference could be explained by motor diesel being less price sensitive than gasoline and/or by substitution between these two fuels. Estimates for gasoline demand in the UK include those obtained by Drollas (1984), using data for 1950-80, of around -0.3 and -0.6 in the short and long run respectively, and by Dargay (1990) of -0.2 and -1.3 for data from 1960-85.[17]

The reversible models estimated in this study indicate, however, that there was a structural shift in 1975, and are rejected in favour of one including P_m. Including P_m (model C) or allowing for differential intercepts have basically the same effect: the price elasticities are reduced to about -0.06 and -0.1 in the short and long run respectively. However, the standard errors of these estimates are rather large, so that based on our estimates there is a high probability that the long-run elasticity is not different from zero. There is some support for these results in recent study of UK gasoline demand by Rice and Frater (1989). On the basis of monthly data for the period 1977-86, they estimate long-run price elasticities of -0.17 and -0.13, depending on whether or not a car-efficiency term is included in the model. These are clearly much lower than the "consensus" estimates reported

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16 With a simple reversible partial adjustment model, we find price elasticities of -0.1 and -0.5 in the short and long run respectively.

17 My earlier study indicates a very low price elasticity for diesel in the UK, so that the implied price elasticity for total oil demand for road transport would be reduced to -0.9. The remaining difference between this estimate and those presented in the present study based on reversible models is primarily explained by the fact that the former is based on a data sample that does not include the price collapse.

above; and according to our results, they should be, since the 1974-5 price increases are not included.

A number of studies of oil demand for road transport reported in the literature also test for structural stability. Dargay (1990) tests for a structural break in the gasoline demand function between the 1960-73 and 1974-85 sub-periods, and finds significant evidence of this only for Italy and Spain, but not for the UK. However, other sub-periods were not considered, so this does not rule out a break in 1975 as indicated in the present study. In another recent study for the UK, Sandbach (1988) finds stability between the 1968-77 and 1977-86 sub-periods for gasoline, but not for automotive diesel. He does not test for other possible break points, however, so that our evidence of a shift in 1975 is not refuted. The estimates of price elasticities obtained for gasoline by Sandbach are also rather different from those obtained in other studies. Although there is a significant short-run response of -0.2 within three months, the effect is found to be only temporary, with demand returning to its previous level in subsequent periods, so that the long-run elasticity is zero. A similar pattern for the own-price reaction is found for automotive diesel, although the price of gasoline is shown to have a significant positive long-run effect.

Another study that includes tests for structural stability in the UK is that of Abodunde, Wirl and Koestl (1985). Using annual data for transport for 1970-82 the authors find evidence of a structural break in 1974 when GDP is used as an income variable, but not when disposable income is used. These results cannot be strictly compared with ours or those of most other studies, however, since allowance is made only for changes in elasticities and not for changes in intercepts.

Many more studies exist for the US. Bopp (1984), employing F-tests for overall homogeneity between various sub-periods, finds a structural shift in gasoline demand between the pre- and post-embargo periods using aggregate monthly data for 1966-82, but does not report the estimated parameters. These results are supported by Lin, Botsas and Monroe (1985), also using an F-test, for pooled annual time-series cross-section data for 1966-80. These authors attempt to estimate short-run elasticities by including a fuel-efficiency variable, and find that both the intercept and short-run price elasticities are lower for the post-embargo period. Structural instability is also found by Uri and Hassanien (1985) for aggregate monthly data for 1968-83, using recursive regression and the Brown-Durbin-Evans test for structural stability. Their results are rather different from those of the previous authors, however, since a change in the demand relationship is noted only for the post-1979 period, and price elasticities are found to have become larger, not smaller. In other studies for the US, neither Kwast (1980), using regional gasoline data for the period 1973-7, nor Abodunde, Wirl and Koestl (1985), using annual data for transport for 1970-82, find evidence of structural change in 1974, although, as mentioned above, the latter only test for changes in the slope parameters. Although the empirical evidence is somewhat mixed, the majority of studies, in agreement with our own, tend to support the hypothesis of structural change occurring in the mid-1970s.

To summarize the results obtained, the reversibility of oil demand in the transport sector to price changes is rejected on the basis of our data sample. There is strong evidence of a downward shift in the long-run demand curve of 14 per cent coincident with the price rises of 1975 following the first oil price shock. A large part of this shift in demand can probably be explained by technological improvements in vehicle fuel efficiency, which will not be undone, despite falling prices. The results suggest, as well, that demand has been relatively insensitive to previous and subsequent price changes, including to the price collapse of 1986, and that changes in demand during these periods can largely be explained in terms of changes in real income. Although real prices had fallen to nearly their 1973 levels by 1988, there is no evidence of a reversal in the downward shift in the demand relationship. Of course, if prices remain low - as they have done throughout 1989 - for a longer period of time, or fall even further, the long-run demand curve can shift upwards again. Clearly, environmental concerns will also serve as a limiting factor to such a reversal.

5.3 Energy and Oil Demand in the Domestic Sector

(a) Total Energy Demand. The initial specification for total energy demand in the domestic sector included all income and price variables as well as a degree day variable DD. All lagged variables, with the exception of lagged energy consumption E(t-1), were found to have a negligible influence on demand, so that the preferred specification is of the partial adjustment form. The estimates obtained on the basis of this model are presented in Table 5, which also shows the F-tests for the implied restrictions on the initial (unrestricted) dynamic specification. Judging from the F-statistics, we see that the partial adjustment model would not be rejected in favour of the more general dynamic formulation.

Model A includes both P+ and P_m as well as actual prices P, along with the other explanatory variables. We find that the coefficient of the actual price variable, P, is positive, but not statistically significant, whereas those of both P+ and P_m are significant. The coefficient of P_m is positive, however, indicating that price rises of the previous maximum have a smaller effect than other price rises, with a short-run elasticity of -0.01 (-0.56 + 0.55), as opposed to -0.56. In model B, P_m is deleted, which results in only a marginal increase in the standard error, but the coefficients of both P+ and P are not significantly different from zero. Models C and D result from deleting P and P+ respectively. Model C indicates a significant response to rising prices when the response to falling prices is constrained to be zero. Excluding P+, however, results in only slightly smaller (but of course, symmetric) elasticities, while only raising the

Table 5. Energy Demand in the Domestic Sector: Estimated Models. All Models with Energy Consumption as Dependent Variable.

	A		B		C		D	
k	-0.63	(0.42)[1]	1.02	(0.75)	1.39	(1.43)	2.16	(2.16)
E(t-1)	0.85	(6.43)	0.70	(6.00)	0.70	(6.11)	0.70	(5.90)
Y	0.40	(2.01)	0.51	(2.50)	0.46	(2.97)	0.31	(2.40)
P	0.21	(0.97)	0.09	(0.41)			-0.17	(2.13)
P+	-0.56	(2.26)	-0.27	(1.25)	-0.19	(2.51)		
P_m	0.55	(2.02)						
DD	0.21	(3.49)	0.32	(2.71)	0.30	(2.84)	0.26	(2.37)
R^2	0.98		0.98		0.98		0.98	
DW	1.98		1.79		1.76		1.69	
s	0.0246		0.0264		0.0259		0.0267	
RSS	0.01214		0.01462		0.0147		0.01571	
SC	-6.853		-6.991		-7.071		-6.839	
LM(3)					0.09 F(3,19)[2]		0.10 F(3,19)	
F-test for parameter restrictions:								
Unrestricted Model to	1.56 F(9,11)		1.92 F(10,11)		1.77 F(11,11)		1.95 F(11,11)	
Model A to			4.09 F(1,20)		2.11 F(2,20)		2.94 F(2,20)	
Model B to					0.04 F(1,21)		1.57 F(1,21)	
Chow-test (1962-85 vs 1986-8)					2.64 F(3,19)		3.92 F(3,19)*[3]	
RESET-Y^2					0.20 F(1,21)		15.4 F(1,21)**	
RESET-t					0.62 F(1,21)		0.4 F(1,21)	
Price Elasticity					P+	P-	P	
Short-run					-0.19	0	-0.17	
Long-run					-0.63	0	-0.57	
Income Elasticity								
Short-run					0.46		0.31	
Long-run					1.53		1.03	

Notes: 1. t-values.
2. Distribution and degrees of freedom for test statistics.
3. * and ** denote that test statistics are significant at the 95 and 99 per cent confidence levels respectively.

standard error marginally, so the choice of model is not so clear cut. Both models are deemed acceptable on the basis of LM tests and the RESET test does not indicate the significance of a time trend in either model. The functional form of the model excluding P+ is rejected, however, on the basis of the RESET test for adding $\hat{Y}^2$. The recursive Chow-tests in Figures A7 and A8 in the appendix indicate that the estimates are stable over all but the last few years of the observation period. The Chow-test statistics for structural change between the pre-1986 and the 1986-8 periods reproduced in Table 5 clearly reject parameter constancy between these two periods in the reversible specification, which calls into question the validity of this model in explaining the response to the recent price falls.

The estimated elasticities for the reversible and irreversible models are very similar, about -0.2 and -0.6 in the short and long run respectively. For the irreversible specification, model C, these apply only to rising prices, whereas for price falls, the elasticity is zero. The income elasticity is greater in the irreversible model, however, which seems to compensate for the effects of falling prices in the reversible model.

The estimated price and income elasticities for both models are of reasonable magnitude and well in agreement with those obtained in other studies.[18] For the UK, the Department of Energy (1989) reports price elasticities for residential space and water heating of -0.2 and -0.4 in the short and long run respectively, and corresponding income elasticities of 0.5 and 0.9. There are only a few studies of energy demand in the residential sector that test for structural stability, and most of these are for electricity demand in the US.[19] In a study for the US, Dunstan and Schmidt (1989), reject structural stability between the pre- and post-1974 periods

[18] See, for example, Kouris (1983) for a survey of energy demand elasticities, which includes the residential sector.
[19] See, for example, Stevens and Adams (1987) and Chern and Bouis (1988).

using Chow-tests for oil and electricity but not for gas. For residential energy demand in Canada, Watkins and Waverman (1987), using a variation of a "captive" demand model, conclude that the long-run price elasticity for a period of falling prices following a period of rising prices is lower than that for periods of rising prices.

In summary, the empirical results call into question the reversibility of energy demand in the domestic sector. The irreversible specification, model C, is preferred to a reversible specification on the basis of the statistical criteria applied. However, certain reservations must be made, since the reversible specification performs nearly as well.

(b) Oil Demand. Although oil accounts for only a small proportion of energy use in the domestic sector, demand has changed considerably over the past three decades. Oil consumption increased threefold between 1960 and 1973, from less than 5 per cent to slightly more than 11 per cent of total domestic energy use. From 1974 to 1983 consumption decreased in absolute terms, as well as in relation to gas and electricity. Although demand rose marginally after 1983, it has remained at just under 6 per cent of total energy consumption.

The initial model for domestic oil demand included the prices of gas and electricity and a degree day variable DD, along with oil prices and income. None of the estimated models performed particularly well. The prices of gas and electricity were not significant in any of the formulations, and none of the specifications including lagged exogenous variables gave reasonable results.

The estimates for the partial adjustment model are shown in Table 6. Since most price rises during the period resulted in price levels above the previous maximum, we cannot distinguish between P+ and P_m. The inclusion of P_m was slightly preferred, so only the models including P_m are presented. Model A includes the price of gas P_g as well as the oil prices P and P_m. We see that the coefficients of P_g

and P are of the wrong sign, but neither is significantly different from zero. Deleting P_g (model B) is not rejected on the basis of the F-test, and does not change the estimated parameters significantly. Neither the LM-test for residual correlation, nor the RESET tests lead to rejection of this model. Deletion of P_m, resulting in Model C, however, increases the estimated standard error substantially and is rejected by the F-tests.

The recursive Chow-tests for models B and C are shown in Figures A9 and A10 in the appendix. Neither model is stable over the entire observation period, although the model including P_m appears to be somewhat better. The recursive estimation of model B also indicates an increase in the coefficient of P_m for the period from 1978 onwards. To test this a new price variable was included, taking the value of P_m for the period 1978-88 and zero otherwise. The results are presented as model D in Table 6. If the price rises of 1979-82 had a different effect than those of 1974-7, we would expect this variable, denoted P_m(79-82), to be significant. (Since real prices fell over the period 1983-8, P_m is constant from 1982 onwards.) We find that P_m(79-82) is negative and statistically significant, suggesting that the 1979-82 price rises have had a greater effect than those of 1974-7. The coefficient of P is still positive, however, but now significantly so, indicating that price decreases lead to a decrease in demand, which is clearly unacceptable. The income elasticity is again rather high, and similar to that obtained in model B. Although the model cannot be rejected on the basis of the statistical tests and the F-test shows it to be preferable to model B, the positive own-price elasticity for price decreases and increases below the previous maximum questions the validity of the model.

In conclusion, the empirical results lend some support to the irreversibility of oil demand in the domestic sector. The estimates suggest that the price rises of the mid-1970s/early 1980s have had a substantial effect on demand, with the second price shock having a somewhat greater effect

Table 6. Oil Demand in the Domestic Sector: Estimated Models. All Models of Partial Adjustment Form, with Oil Consumption as Dependent Variable.

	A	B	C	D
k	-1.01 (0.99)[1]	-2.33 (2.19)	-0.05 (0.05)	-0.05 (3.48)
E(t-1)	0.66 (5.37)	0.73 (8.87)	0.92 (12.54)	0.57 (6.72)
Y	0.68 (2.79)	0.75 (3.24)	0.05 (0.40)	1.10 (5.03)
P	0.14 (1.58)	0.14 (1.65)	-0.11 (2.40)	0.19 (2.61)
P_g	-0.11 (0.46)			
P_m	-0.53 (3.00)	-0.51 (3.36)		-0.47 (3.68)
DD	0.42 (1.79)	0.43 (1.79)	0.38 (1.32)	0.61 (2.51)
P_m(79-82)				-0.21 (3.29)
R^2	0.92	0.93	0.89	0.95
DW	1.72	1.77	1.41	2.39
s	0.0638	0.0598	0.0724	0.0493
RSS	0.08552	0.07495	0.11533	0.04861
SC	-5.022	-5.154	-4.845	-5.466
LM(3)	0.40 F(3,17)[2]	0.61 F(3,18)	1.17 F(3,19)	2.62 F(3,17)
F-test for parameter restrictions:				
Model A to		2.11 F(1,20)	3.49 F(2,20)	
B to			10.24 F(1,19)**[3]	
to Model B				10.30 F(1,19)**
RESET-$\hat{Y}^2$		0.80 F(1,20)	3.83 F(1,21)	0.42 F(1,19)
RESET-t		0.45 F(1,20)	1.46 F(1,21)	0.45 F(1,19)

	B: P_m	B: P	C: P	D: P_m	D: P_m(79-82)
Price Elasticity					
Short-run	-0.51	(0.14)[4]	-0.11	-0.47	-0.68
Long-run	-1.89	(0.56)	(-1.37)	-1.09	-1.58

	B	C	D
Income Elasticity			
Short-run	0.75	(0.05)	1.10
Long-run	2.78	(0.63)	2.56

Notes: 1. t-values.
2. Distribution and degrees of freedom for test statistics.
3. * and ** denote that test statistics are significant at the 95 and 99 per cent confidence levels respectively.
4. Elasticities in parentheses are based on non-significant parameter estimates.

than the first price shock. In addition, there is evidence that demand has been completely insensitive to previous and subsequent price falls, indicating that the price increases have had a permanent dampening effect. However, given the inadequacy of all the estimated models, and particularly the unreasonably high income elasticities, our conclusions concerning the irreversibility of oil demand in the domestic sector must be a bit tentative.

6 CONCLUSIONS

In the preceding sections we have presented and discussed the empirical results obtained from the estimation of a number of energy demand functions for the UK. The most general model specifications explicitly allow for irreversible price effects by incorporating an identical asymmetric demand response to rising and falling prices at each price level and at each point in time, so that long-run demand is itself determined by its entire price history. With this formulation, from any given price, a period of rising/falling prices followed by a reversion to the initial price will not restore demand to its original level. Particularly, if demand is found to be more sensitive to price increases than to price falls, the long-run decrease in demand resulting from a price rise will not be fully reversed as prices fall to their initial levels. A proportion of the demand reduction will thus be irreversible. If, on the other hand, demand is equally responsive to rising and falling prices, demand will be totally reversible.

Both the irreversible and reversible models were evaluated in terms of goodness of fit, statistical tests for the validity of the restrictions imposed, the statistical characteristics of the error term, functional misspecification and parameter constancy. The preferred models were chosen on this basis, along with the plausibility of their economic implications.

Although the results presented can certainly not be considered "definitive" elasticity estimates, they do throw considerable light on the issue at hand - the reversibility of energy demand to changing prices. The empirical evidence raises serious doubts regarding the validity of using an unchanging, purely reversible demand function to explain the energy consumption patterns of the past thirty, or even twenty years. In most instances, such demand functions are found to exhibit substantial parameter instability, particularly at the outset of changing price regimes - as in the mid- or late 1970s and/or the late 1980s. Especially apparent are downward shifts in both the long-run total energy demand function and the long-run oil demand function in the transport sector, coincident with the price shock of the mid-1970s.

In all cases, an irreversible specification that allows for asymmetric price effects is favoured over the reversible model, so that the reversibility of energy demand is refuted. For some of the demand models, particularly oil in the transport sector and total oil and energy, the evidence is much stronger than for others. Generally, the estimates indicate that demand has not responded symmetrically to rising and falling prices. Over the period estimated, demand appears to have been extremely sensitive to price increases, while price decreases have had only marginal effects. In most instances, the results indicate that price decreases have had only a small, and relatively short-lived, impact on demand, so that the initial response is negated over time as consumption returns to its initial level.

Although these results imply that the reductions in energy demand witnessed since the mid-1970s are completely irreversible, we should be somewhat tentative about drawing this conclusion. As we have shown in Section 4, the extent and rapidity of the 1986 price collapse is unprecedented. It is possible that, as a result, consumer response to it has been quite different from that to previous price falls, even though there is no statistically grounded indication of this in the time-period under consideration. One possibility may be that the reaction has been delayed, so that our sample period may be insufficient to capture the true long-run response. The inclusion of post-1988 data may yet provide evidence of a significant long-run response to the price collapse and of a partial reversion of the decline in consumption associated with the price rises.

As the irreversible specifications indicate only a marginal response to falling prices, the increase in demand noted during the past few years cannot be explained in terms of the price collapse. Instead, the estimates suggest that the renewed growth in demand can be attributed almost entirely to an increase in economic activity. Again, a word of caution must be given about this result. In some cases, particularly those of total oil demand and oil demand in the domestic sector, the estimated long-run income elasticities are rather higher than one would expect, and generally higher than those obtained on the basis of the reversible models. This may be an indication that we are partially confusing the effects of income increases and of price falls. However, we find that the income elasticities are not significantly different from zero in three of the five reversible models estimated, which seems to suggest that an over-estimation of the demand response to falling prices may be compensated by a reduction in the income effect. Although there is no indication of a change in the income elasticity over the observation period in any of the models, a decreasing elasticity may partially explain our findings.

In some of the models, we have been able to distinguish between the effects of general price rises, and those where prices reach a higher level than previously during the period under consideration. For oil demand in the transport sector, for example, we find that the price effect is largely attributed to the price shocks of 1974-5, while other price rises and price falls have had a far smaller impact on demand. For total oil demand, the results are somewhat different. Although all price increases have reduced long-run oil consumption proportionately, price rises above the previous maximum have had a far greater initial impact than other price rises, and adjustment to equilibrium has been faster. On the other hand, price falls are shown to have only a small short-term effect, with demand returning to its initial levels in subsequent years. The results for oil demand in the domestic sector are also very interesting in that they suggest that demand has responded more to the second than to the first oil price shock, although not at all to price falls.

Another result of the study concerns the dynamics of energy demand. For total energy and oil demand and for oil demand in the transport sector, the partial adjustment specification is clearly rejected in favour of a model containing a more general lag specification. Particularly, there appears to be an initial over-reaction to price increases, so that the short-run reduction in consumption is lessened over time as consumers adapt to the higher prices. Consumption then begins to decline again as longer-run adjustments could be made, presumably in connection with capital investments, so that the total long-run effect is considerably greater.

Finally, the results obtained in this study strongly question the validity of using estimates based on reversible models estimated on pre- and post-1974 data in forecasting energy demand, particularly for a future characterized by lower energy prices. The data clearly suggest that such elasticity estimates largely reflect the effects of the price shocks of the 1970s, and as such will give a poor indication of how demand will respond to falling prices, or even to smaller price increases. There is a clear indication that the reductions in energy demand that have taken place over the past fifteen years will not be totally reversed - at least in the foreseeable future - unless real prices fall well below the levels prevailing in the early 1970s. As the empirical results are based solely on UK data, our conclusions concerning the irreversibility of energy demand pertain only to the UK. Similar studies of other countries would need to be carried out in order to ascertain whether our findings are peculiar to the UK or if they have more general implications.

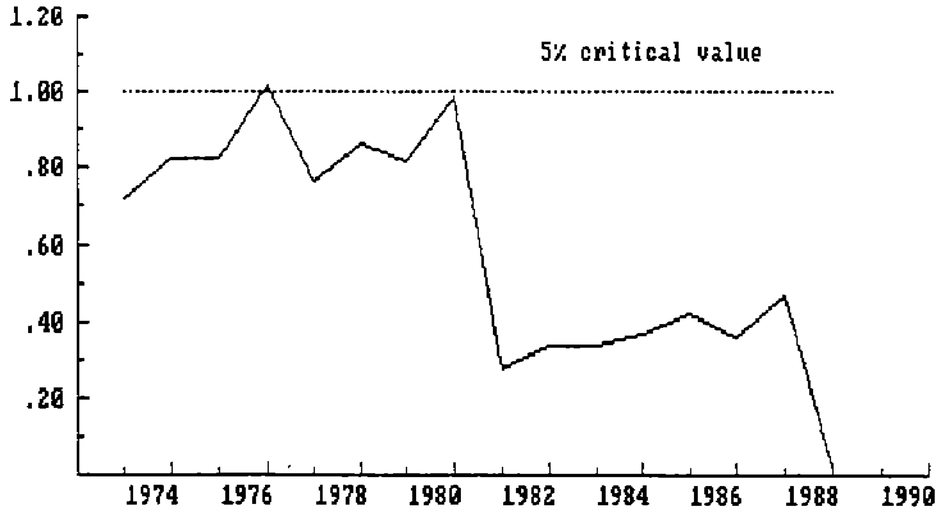

Figure A1: Recursive Chow-tests for Total Final Energy Demand (scaled by 5 per cent Critical Value). Table 1, Model C(+). 1973-88.

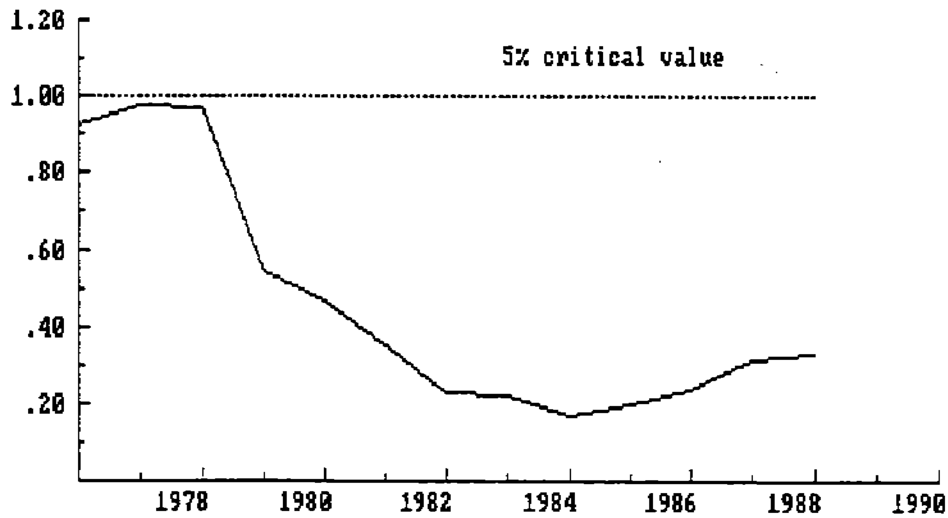

Figure A2: Recursive Chow-tests for Total Final Energy Demand (scaled by 5 per cent Critical Value). Table 2, Model C(m). 1976-88.

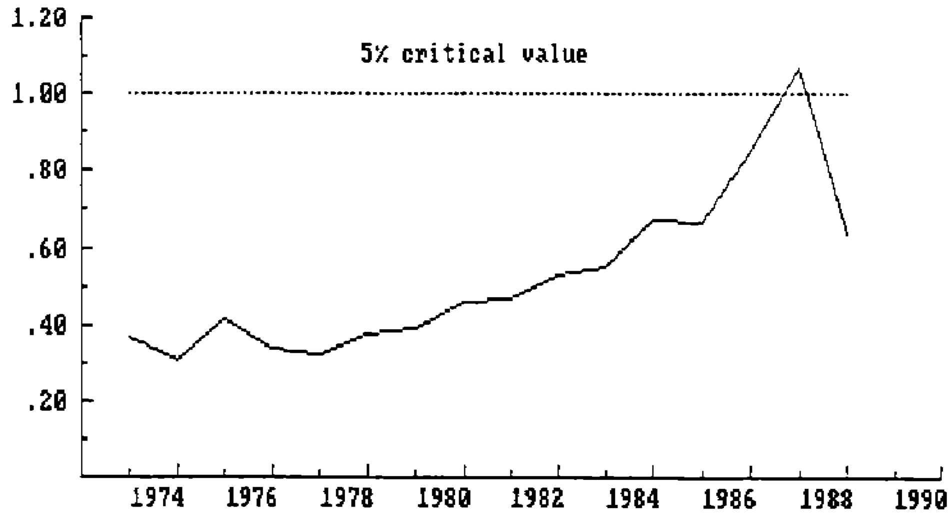

Figure A7: Recursive Chow-tests for Energy Demand in the Domestic Sector (scaled by 5 per cent Critical Value). Table 5, Model C. 1973-88.

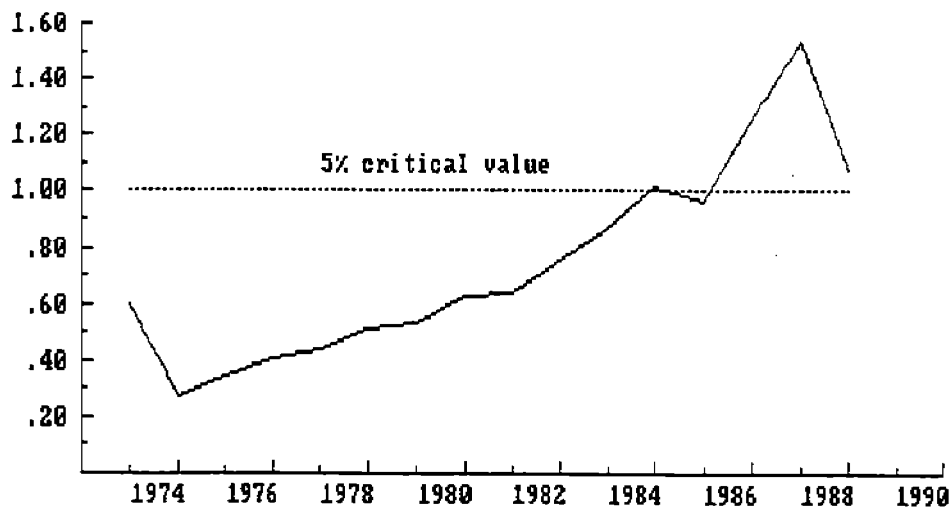

Figure A8: Recursive Chow-tests for Energy Demand in the Domestic Sector (scaled by 5 per cent Critical Value). Table 5, Model D. 1973-88.

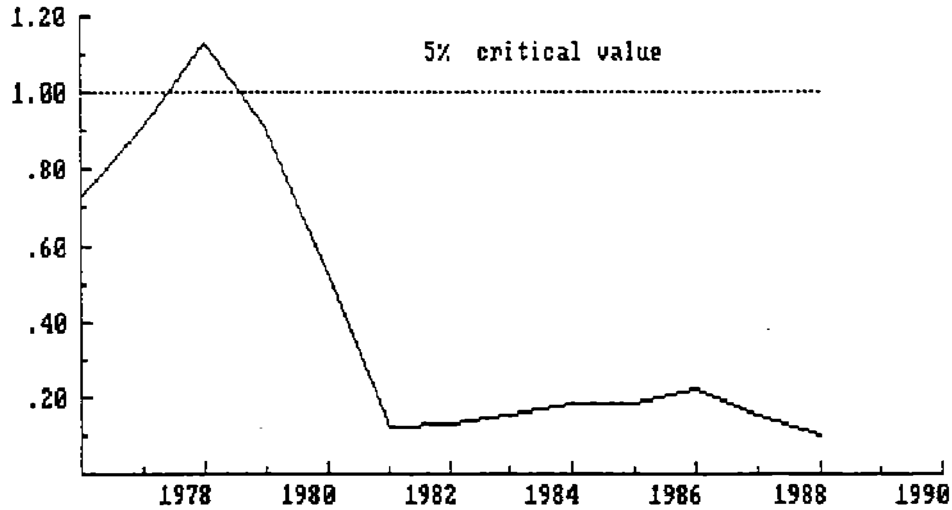

Figure A9: Recursive Chow-tests for Oil Demand in the Domestic Sector (scaled by 5 per cent Critical Value). Table 6, Model B. 1976-88.

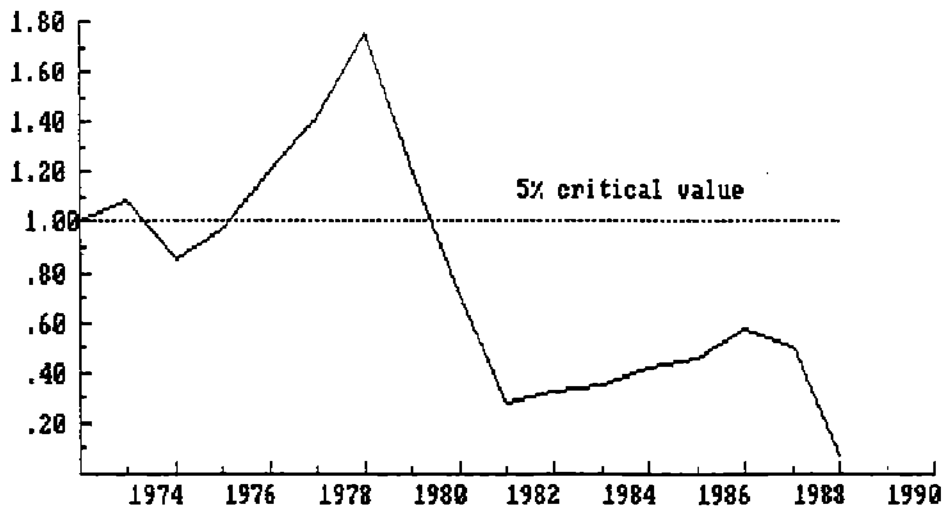

Figure A10: Recursive Chow-tests for Oil Demand in the Domestic Sector (scaled by 5 per cent Critical Value). Table 6, Model C. 1972-88.

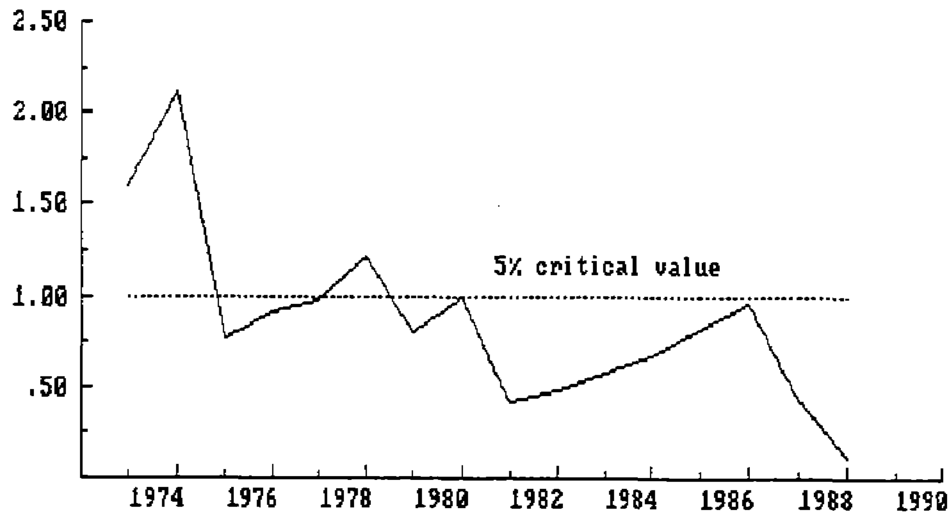

Figure A3: Recursive Chow-tests for Total Final Energy Demand (scaled by 5 per cent Critical Value). Table 1, Model D. 1973-88.

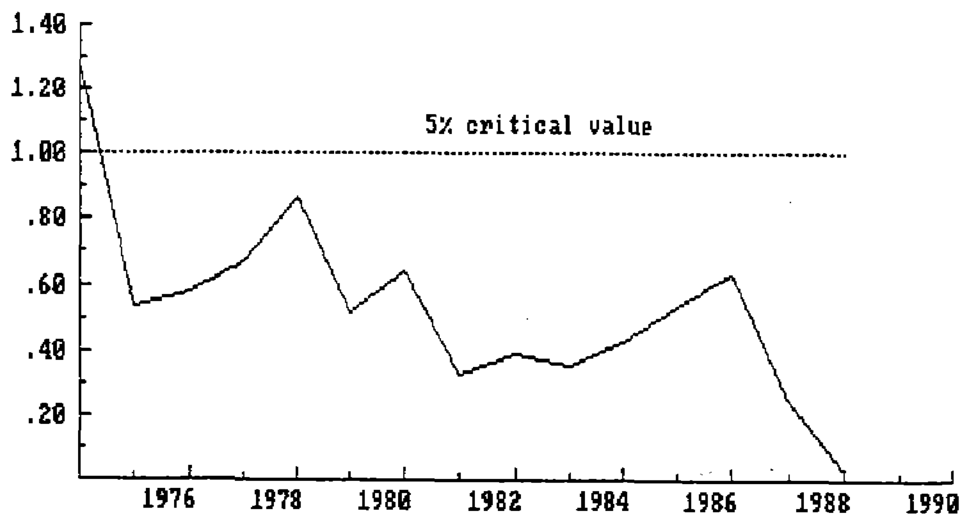

Figure A4: Recursive Chow-tests for Total Final Energy Demand (scaled by 5 per cent Critical Value). Table 2, Model E. 1974-88.

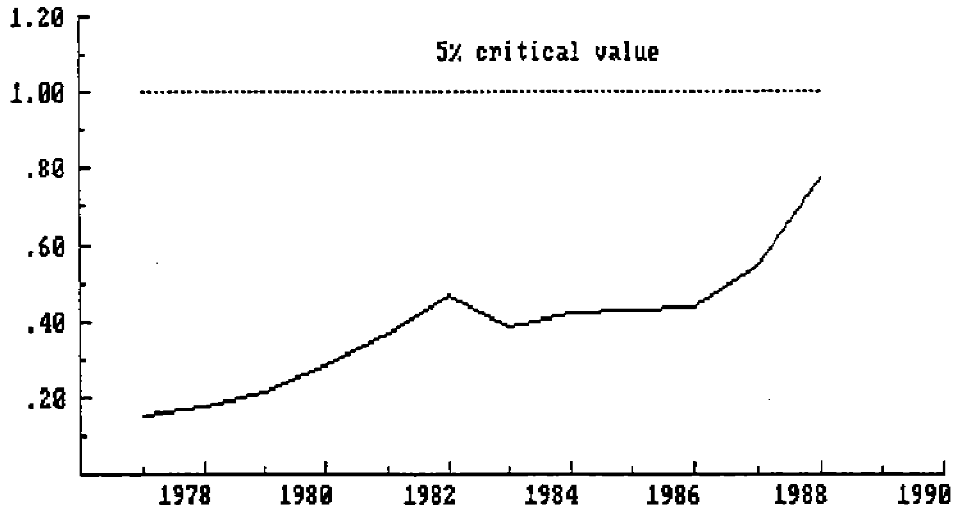

Figure A5: Recursive Chow-tests for Total Final Oil Demand (scaled by 5 per cent Critical Value). Table 3, Model B. 1974-88.

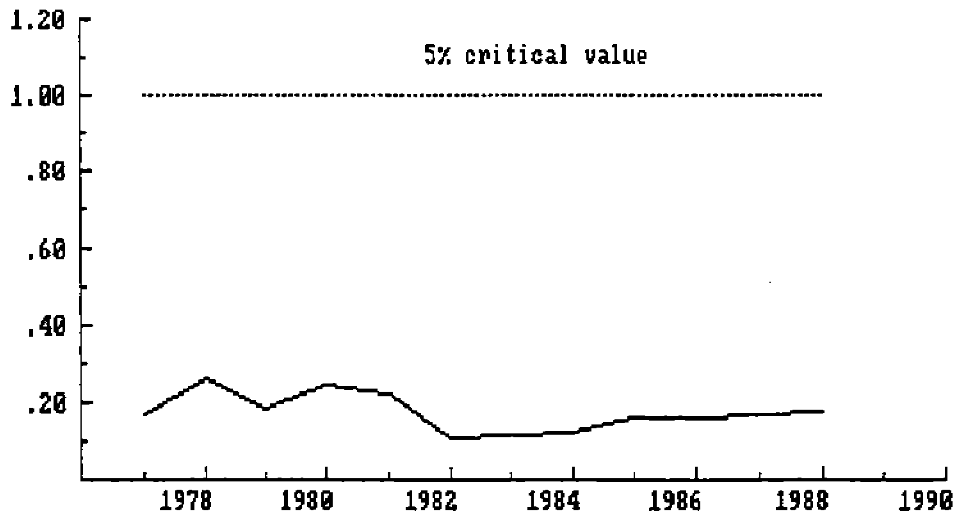

Figure A6: Recursive Chow-tests for Oil Demand for Road Transport (scaled by 5 per cent Critical Value). Table 4, Model C. 1977-88.

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